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INVESTIGATION OF STRIPPING OF VOLATILE ORGANIC CONTAMINANTS IN MUNICIPAL WASTEWATER TREATMENT SYSTEMS - PHASE II

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INVESTIGATION OF STRIPPING OF VOLATILE ORGANIC CONTAMINANTS IN MUNICIPAL WASTEWATER TREATMENT SYSTEMS - PHASE II

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Environment Canada

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EXECUTIVE SUMMARY

The stripping of volatile organic compounds (VOCs) from municipal wastewater treatment plants was studied at pilot plant and full scale. The study complemented an earlier full scale sampling program (Bell et al., 1988). The objectives of the study were:

- To validate the accuracy of sampling and analytical protocols used in the full scale sampling program.
- To determine the relative importance of three potential removal mechanisms for VOCs from activated sludge aeration basins: stripping, biological removal and sorption on secondary sludge.
- To examine the impact of the following design and operation variables on VOC stripping: diffuser type (fine or coarse bubble diffusers), airflow rate and solids retention time.

Experiments were first conducted at pilot scale. The stripping of volatiles in the absence of biomass was assessed using tap water dosed with ten candidate VOCs as the primary effluent fed to the aeration basin. In the second set of experiments the pilot plant received a continuous supply of wastewater from the Burlington Skyway Water Pollution Control Plant and was maintained at a 5 day solids retention time. Both dosed and non-dosed wastewater experiments were performed at low and high airflow rates using alternately fine and coarse bubble diffuser systems. Select experiments were repeated at a 10 day solids retention time. In the final set of experiments the pilot plant received a continuous supply of wastewater from the Highland Creek Water Pollution Control Plant and was operated in parallel with a full scale Highland Creek aeration basin. In each set of experiments the pilot plant matched the conventional pollutant and VOC treatment efficiency of the full scale plant. Oxygen transfer tests and

hydraulic studies were carried out in each set of experiments to establish the stripping conditions.

For each pilot plant experiment, a mass balance was performed around the aeration basin using measured influent, effluent, waste activated sludge and off-gas concentration measurements. An average VOC mass balance closure of 84% was achieved during dosed tap water experiments suggesting acceptable sampling and analytical accuracy. A high percentage of the influent VOC mass flowrate was stripped from the aeration basin during dosed tap water experiments. In wastewater studies, the mass balance closure for 15 non-chlorinated VOCs was less than 10% suggesting substantial biological removal of these VOCs. The mass balance closures for 7 chlorinated VOCs were lower than those observed during dosed tap water experiments suggesting that limited biological removal of these VOCs was occurring, but that stripping was a major removal mechanism for these VOCs. There was little evidence of greater biological removal at the 10 day solids retention time than at the 5 day solids retention time. Adsorption on to waste activated sludge was not a major removal mechanism for any VOC investigated.

In the pilot plant experiments it was observed that the amount of stripping increased with increasing airflow rate, but the relative increase in percentage stripped was less than the relative increase in airflow rate. At airflow rates of 0.05 m^3/m^3min or lower, less than 5% of the influent mass flow of the non-chlorinated VOCs entering the aeration basin was stripped because of competing biological removal. A significant percentage of the influent mass flow of the chlorinated VOCs was stripped from the aeration basin at all airflow rates.

In the pilot plant, the greater gas-liquid phase mass transfer efficiency of the fine bubble diffuser system did not increase the gas phase partitioning of the VOCs. Generally, there was no change

in the gas phase partitioning of the VOCs across the typical range of gas-liquid phase mass transfer conditions encountered in full scale plants. This suggests that the gas and liquid phases were in equilibrium under all conditions although the observed gas phase VOC concentrations differed from those predicted using Henry's Law coefficients obtained from the literature. In the parallel pilot plant/full scale aeration basin experiments at Highland Creek there was no difference between the gas-liquid phase partitioning observed in the pilot plant and the full scale aeration basin suggesting that the full scale and pilot plant sampling protocols were equivalent.

Reductions in airflow rate such as could be achieved with computerized DO control or the installation of more efficient diffuser systems (e.g. fine bubble diffuser systems that can maintain adequate DO at lower airflow rates than coarse bubble diffuser systems) will minimize the stripping of VOCs from activated sludge aeration basins. As observed in the pilot plant, this would likely ensure that less than 5% of the influent mass flow of non-chlorinated VOCs entering the aeration basin would be stripped. However, as also observed in the pilot plant, a substantial percentage of the influent mass flow of the chlorinated VOCs would be stripped even under these optimal conditions.

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INVESTIGATION OF STRIPPING OF VOLATILE ORGANIC CONTAMINANTS IN MUNICIPAL WASTEWATER TREATMENT SYSTEMS

PHASE II

1. INTRODUCTION

1.1 Project Background

Volatile organic contaminants (VOCs) are the largest group of compounds on the Ontario Ministry of Environment (MOE) Effluent Monitoring Priority Pollutant List (Ontario Ministry of Environment, 1988a). These contaminants are among the most frequently detected in raw wastewater and their removal by treatment facilities is a major concern in Ontario's Municipal Industrial Strategy for Abatement (MISA) program.

VOCs may be stripped from wastewater during aeration, and the release of VOCs to the atmosphere is a potential environmental hazard. Accordingly, in 1987, Environment Canada's Wastewater Technology Centre (WTC) sampled the off-gas at four Ontario municipal wastewater treatment plants on behalf of the MOE as the first phase of an investigation of VOC stripping at water pollution control plants (WPCPs).

It was concluded in the Phase I study that many VOCs are stripped from wastewater treatment plants (Bell et al., 1988), and a pilot plant study (Phase II) was recommended to characterize the behaviour of VOCs in activated sludge aeration basins. Sampling and analytical protocols, biological and physical removal mechanisms and the effects of plant operation and design variables on emission rates were identified as major parameters for investigation. Parallel pilot plant and full scale aeration basin sampling was recommended to ensure that the pilot plant adequately represented full scale operating conditions and that the full scale and pilot plant sampling protocols were equivalent.

The second phase of these investigations was carried out on behalf of the Ontario MOE by Environment Canada's Wastewater Technology Centre during the period January 1988 through April 1989.

1.2 Project Objectives

The objectives of Phase II were:

a. To validate the accuracy of sampling and analytical protocols used in Phase I.

b. To determine the relative importance of three potential removal mechanisms for VOCs from activated sludge aeration basins: stripping, biological removal and sorption on to secondary sludge.

c. To examine the impact of the following design and operation variables on VOC stripping: diffuser type (fine or coarse bubble diffusers), airflow rate and solids retention time (SRT)

1.3 Project Scope

An experimental design was developed that utilized three groups of experiments summarized in Table 1.1. In the first set of experiments (II-A), the stripping of VOCs from water, in the absence of biomass, was assessed by using tap water dosed with ten candidate VOCs as the aeration basin influent. Compounds representing a broad range of chemical structure that were consistently observed in the influents sampled during Phase I were selected for dosing. For each VOC, a mass balance was performed around the aeration basin using the aeration basin influent, secondary settler effluent, and aeration basin off-gas VOC concentration measurements. The mass balance closure was used as a measure of the accuracy of the sampling and analytical protocols. Experiments were performed alternately with the coarse and fine bubble diffuser systems at low and high air flowrates to determine the effects of diffuser type and airflow rate on stripping rates.

Table 1.1-Phase II Experimental Plan

Phase II-A Dosed Tap Water

Principal Experiments:
-pilot plant VOC sampling

Ancillary Experiments:
-pilot plant hydraulic study
-pilot plant oxygen transfer testing

Phase II-B Burlington Skyway WPCP Wastewater

Principal Experiments:
II-B.1- pilot plant VOC sampling (dosed and non-dosed wastewater; 5 day SRT)
II-B.2- pilot plant VOC sampling (dosed wastewater; 10 day SRT)
II-B.3- full scale aeration basin sampling

Ancillary Experiments:
-full scale aeration basin hydraulic study
-pilot plant and full scale aeration basin oxygen transfer testing

Phase II-C Toronto Highland Creek WPCP Wastewater

Principal Experiments:
II-C.1- pilot plant VOC sampling (non-dosed wastewater; 5 day SRT)
II-C.2- parallel pilot plant/full scale aeration basin VOC sampling

Ancillary Experiments:
-full scale aeration basin hydraulic study
-pilot plant and full scale aeration basin oxygen transfer testing

Oxygen transfer efficiency tests were performed with the coarse and fine bubble diffusers to establish the gas-liquid phase mass transfer conditions. A dye study was used to establish the mixing regime of the pilot plant aeration basin.

The second set of experiments (II-B) examined the removal of VOCs in the presence of activated sludge. The plant was operated using a continuous supply of raw, degritted wastewater from the Burlington Skyway Water Pollution Control Plant (WPCP) and was maintained at a 5 day SRT (II-B.1). Experiments were later repeated at a 10 day SRT (II-B.2). The same ten candidate VOCs were dosed into the primary effluent and a mass balance was performed around the aeration basin. The sorption of VOCs on to waste activated sludge was also considered in these mass balances. VOC mass balances were also performed when the primary effluent was not dosed with VOCs to ensure that VOC removals were not inadvertently influenced by using VOC dosing levels beyond those at which the sludge was acclimated. A comparison of the mass balance closures between Phases II-A and II-B indicated the amount of biological removal for each VOC. Many VOCs, other than the ten candidates, were detected in the pilot plant influent and were included in the experimental analysis. Experiments were again performed at low and high airflow rates with both diffuser types. Pilot plant oxygen transfer efficiency tests were performed with the process water. Finally, sampling was carried out at a Burlington Skyway WPCP aeration basin (II-B.3), and the VOC emissions were compared to the pilot plant results. A hydraulic study and oxygen transfer efficiency tests were also carried out at the full scale aeration basin to establish the stripping conditions.

In the third set of experiments (II-C), the pilot plant was moved to the Toronto Highland Creek WPCP to allow for a comparison of results with a different wastewater source. The Toronto

Highland Creek WPCP receives 22% of its raw wastewater from industrial sources while the Burlington Skyway WPCP receives 18% of its raw wastewater from industrial sources (Ontario Ministry of The Environment, 1988b). At the Toronto Highland Creek WPCP, the pilot plant received a continuous supply of non-dosed primary effluent and was maintained at a 5 day SRT (II-C.1). Experiments were conducted with both diffuser types at low and high airflow rates, and the mass balance closures were compared to those observed in Phases II-A and II-B. Pilot plant oxygen transfer efficiency tests were repeated because the wastewater source can affect gas-liquid phase mass transfer. In the final set of experiments (II-C.2) the pilot plant was operated in parallel with a Toronto Highland Creek WPCP aeration basin. VOC emissions were measured simultaneously from the pilot plant and the full scale aeration basin to verify that the pilot plant represented full scale operating conditions and that the pilot plant and full scale sampling protocols were equivalent.

1.4 Report Outline

This report complements the Phase I report (Bell et al., 1988). A literature review is contained in the Phase I report and will not be repeated here. Chapter 2 presents details of the experimental procedures used. Attention is focused upon those procedures used in VOC sampling and analysis. Ancillary procedures (i.e. oxygen transfer efficiency tests, hydraulic tests) are described briefly in Chapter 2 and are presented in more detail in report appendices. Chapter 3.1 presents the conventional operating parameters for the pilot plant and full scale aeration basins and summarizes their conventional treatment performance. Chapters 3.2, 3.3 and 3.4 present VOC emission results from Phases II-A, II-B and II-C. Extensive use of report appendices is made to present raw data. Chapter 4 summarizes the study results. Chapter 5 presents the study conclusions and recommendations.

2. MATERIALS AND METHODS

2.1 Pilot Plant Description

The pilot plant consisted of a 5 m^3, 3 m deep aeration basin with primary and secondary settlers each 1.5 m diameter and 2 m deep (Figure 2.1). Provision was made for the continuous dosing of VOCs into the primary effluent. The aeration basin was equipped with coarse and fine pore diffused aerators which could be operated independently. The coarse bubble system consisted of four Napier-Reid, "Invertofuser" diffusers placed in a square pattern elevated 10 cm off the tank bottom. The fine bubble system consisted of four Wyss "Flex-A-Tube" diffusers arranged in a cross pattern between the coarse bubble diffusers. The pressure and temperature of the air entering the diffusers and the air leaving the aeration basin were continuously monitored using thermocouples and pressure gauges. The air entering the diffusers was generally under moderate pressure (approximately 5 psig). The volumetric air flow rate entering the diffusers was measured using a rotameter. The volumetric air flow rate leaving the aeration basin was calculated from the volumetric air flow rate entering the diffusers by assuming an ideal gas relationship to correct for the difference in temperature and pressure. Plant influent and return activated sludge (RAS) flowrates were continuously monitored using magnetic flowmeters. Influent temperature, pH and dissolved oxygen concentration in the aeration basin were also continuously monitored. Details of apparatus used to dose VOCs into the primary effluent and to sample the off-gas from the aeration basin are presented separately in Sections 2.3 and 2.4 respectively.

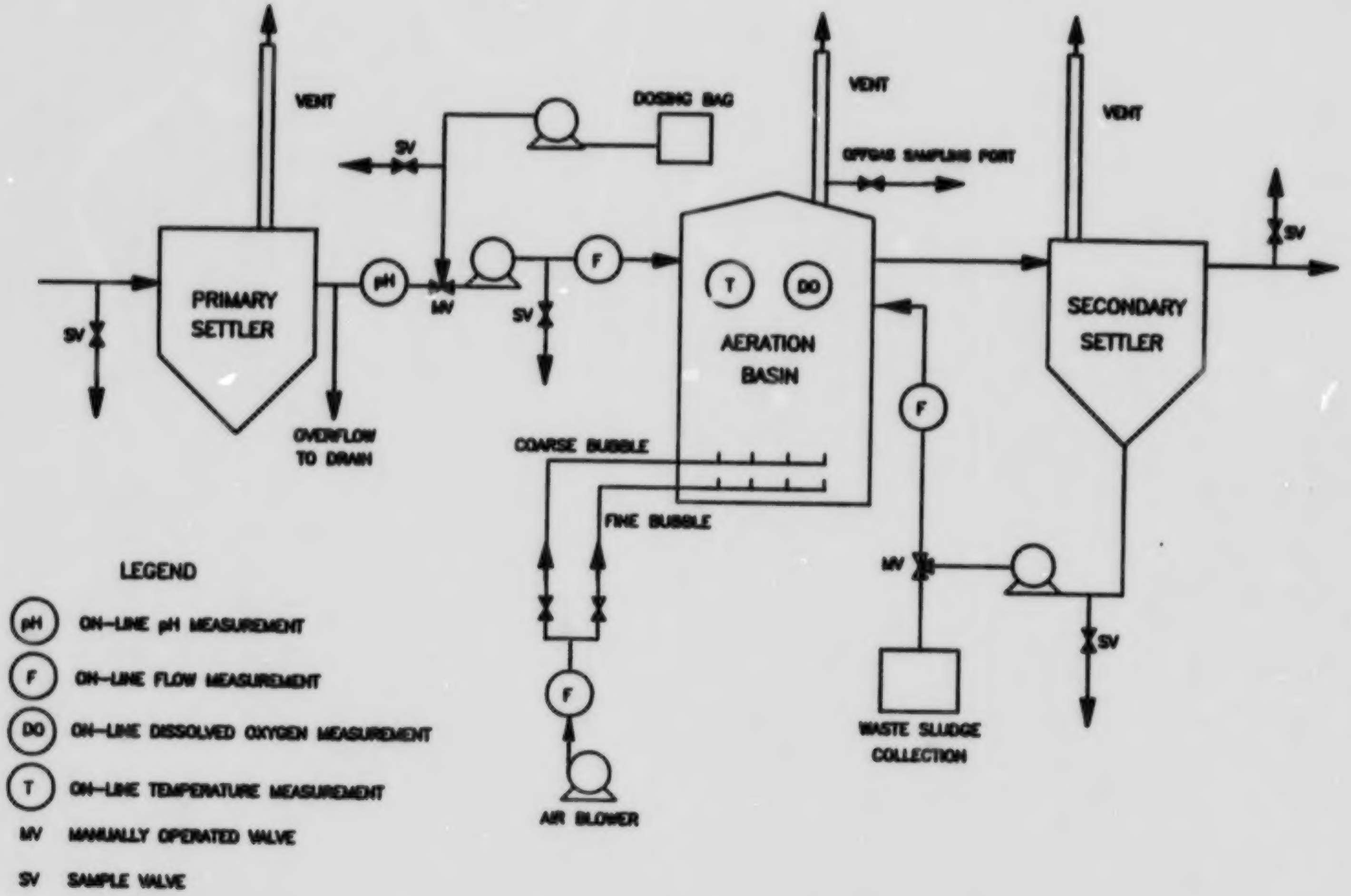

VENT
DOSING BAG
VENT
VENT
SV
OFFGAS SAMPLING PORT
SV
PRIMARY SETTLER
pH
MV
F
T
DO
AERATION BASIN
SECONDARY SETTLER
SV
SV
F
OVERFLOW TO DRAIN
COARSE BUBBLE
FINE BUBBLE
MV
SV
F
WASTE SLUDGE COLLECTION
AIR BLOWER
LEGEND
pH ON-LINE pH MEASUREMENT
F ON-LINE FLOW MEASUREMENT
DO ON-LINE DISSOLVED OXYGEN MEASUREMENT
T ON-LINE TEMPERATURE MEASUREMENT
MV MANUALLY OPERATED VALVE
SV SAMPLE VALVE

Figure 2.1 Pilot Plant Schematic

2.2 Experimental Procedure

2.2.1 Sampling Protocol; Pilot Plant Dosed Tap Water Experiments (Phase II-A)

In Phase II-A, the pilot plant was operated indoors at the WTC and received a continuous supply of Burlington tap water. The overflow from the pilot plant primary settler (tap water) emptied into an overflow tank and was pumped at a controlled rate into the aeration basin. During experiments, VOCs were continuously injected into the primary effluent for 26 hours which represented approximately 4 hydraulic residence times (HRTs) of the pilot plant aeration basin and secondary settler. The VOC concentrations achieved through dosing were much higher than the background tap water concentrations. The aeration basin off-gas was continuously sampled between the 25th and 26th hour of dosing. Liquid samples were taken from the influent to the aeration basin and the secondary settler effluent at the beginning and end of the off-gas sampling interval. The airflow rate was maintained at a constant value throughout the dosing period.

2.2.2 Sampling Protocol; Pilot Plant Experiments Using Burlington Skyway WPCP Wastewater (Phases II-B.1 and II-B.2)

In Phase II-B.1, the pilot plant was operated at the WTC and received a continuous supply of degritted wastewater from the Burlington Skyway WPCP located adjacent to the WTC. Effluent from the pilot plant primary settler was fed into an overflow tank and was pumped at a controlled rate into the pilot plant aeration basin. Sludge was wasted from the system daily into a calibrated tank to measure sludge volume for solids retention time (SRT) control. During dosed wastewater experiments, VOCs were continuously injected into the primary effluent for 26 hours which represented approximately 4 HRTs of the pilot plant aeration basin and secondary settler. The aeration basin off-gas was continuously sampled between the 25th and 26th hour of dosing. Liquid samples were taken at the beginning and end of the off-gas sampling interval. For the non-dosed wastewater experiments, the pilot plant aeration basin off-gas was sampled continuously for three hours and aeration basin influent and secondary effluent samples were taken at one hour intervals. For both dosed and non-dosed wastewater experiments, pilot plant return activated sludge samples were taken half way through the off-gas sampling interval.

2.2.2.1 Sampling Protocol; Burlington Skyway Full Scale Aeration Basin Experiments (Phase II-B.3)

At the Burlington Skyway Wastewater WPCP, one of the six aeration basins was sampled. The sampled basin was 80 m long and 8 m wide and was aerated by coarse bubble diffusers arranged symmetrically in nine laterals. Off-gas samples were collected from three 1.49 m^2 floating chambers secured by ropes in the aeration basin.

The sampling chambers were located directly over diffuser laterals 2,5 and 8 (Figure 2.2). Off-gas was sampled for one hour simultaneously from each off-gas sampling chamber. The airflow through each sampling chamber was measured at the end of the off-gas sampling interval. Mixed liquor samples were taken at each off-gas sampling location at the beginning and end of the off-gas sampling interval. The influent to the aeration basin was sampled mid-way through the off-gas sampling interval. The mixed effluent from the secondary settlers was also sampled mid-way through the off-gas sampling interval.

2.2.3 Sampling Protocol; Pilot Plant Experiments Using Toronto Highland Creek WPCP Wastewater (Phase II-C.1 and II-C.2)

The pilot plant was transported to the Toronto Highland Creek WPCP for Phase C. The pilot plant primary settler was not

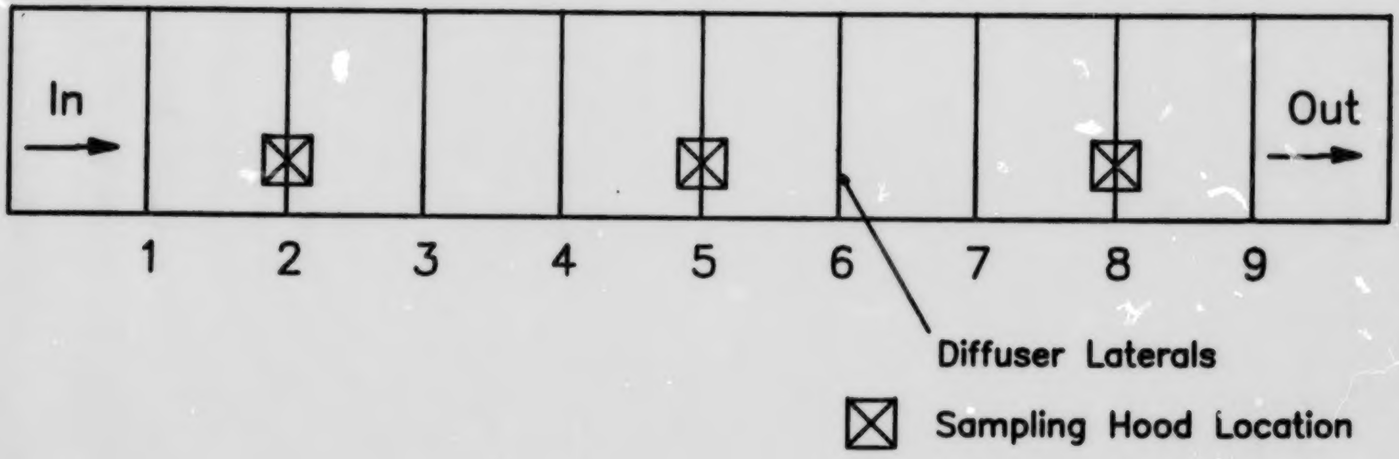

In
Out
1
2
3
4
5
6
7
8
9
Diffuser Laterals
☒ Sampling Hood Location

Figure 2.2 VOC Sampling at Burlington Skyway Water Pollution Control Plant

employed, and a pump submerged approximately 0.5 m in a Toronto Highland Creek primary settler fed primary effluent into an overflow tank where it was pumped at a controlled rate into the pilot plant aeration basin. Sludge was wasted from the system daily into a calibrated tank to measure sludge volume for solids retention time (SRT) control. The pilot plant aeration basin off-gas sampling interval was three hours and pilot plant aeration basin influent and secondary settler effluent samples were taken every hour. A single pilot plant return activated sludge sample was taken mid-way through the off-gas sampling interval.

2.2.3.1 Sampling Protocol; Parallel Pilot Plant/Full Scale Aeration Basin Experiments; Toronto Highland Creek WPCP Wastewater (Phase II-C.3)

The effluent from two Toronto Highland Creek primary settlers, one of which also provided the pilot plant with primary effluent, flowed through a 25 m long common channel to feed four parallel aeration basins. Each aeration basin was 8.8 m wide by 36 m long and had uniform aeration supplied by fine pore diffusers. Off-gas samples from the full scale aeration basin were collected from three 1.49 m^2 floating chambers secured by ropes in the aeration basin. The off-gas chambers were placed in the aeration basin for 24 hours before sampling to ensure that they contained a representative off-gas sample. Off-gas samples were taken from the pilot plant aeration basin vent stack and from the sampling chambers located 1/4, 1/2 and 3/4 along the length of the full scale aeration basin (Figure 2.3). The off-gas was sampled simultaneously for one hour from the pilot plant aeration basin and the three full scale aeration basin sampling locations. The airflow through each sampling chamber was measured at the end of the off-gas sampling interval. Liquid samples were taken from the following locations at the beginning and end of the off-gas

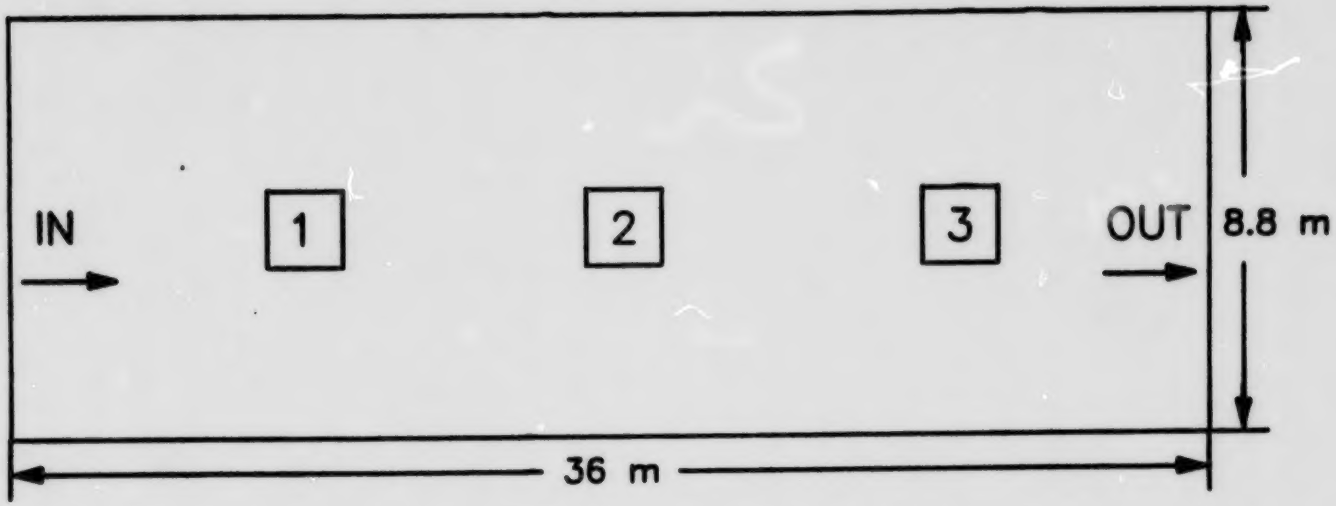

IN
1
2
3
OUT
8.8 m
36 m

Figure 2.3— VOC Sampling At Highland Creek
Full Scale Aeration Basin

sampling interval: pilot plant aeration basin influent, pilot plant secondary settler effluent, full scale aeration basin influent, and mixed liquor samples at the three full scale aeration basin off-gas sampling locations.

2.3 Dosing Procedure

Compounds representing a broad range of chemical structures, that were consistently observed in the influents sampled during Phase I, were selected for dosing. The candidate compounds and the target influent concentrations are shown in Table 2.1a. A summary of the chemical and physical properties of the candidate VOCs is presented in Table 2.1b. It should be noted that there are different sources for Henry's Law coefficients which frequently differ in value. For consistency, all references to Henry's Law coefficients in this report refer to the values expressed in Table 2.1b. Throughout this report Henry's Law coefficients are expressed in units of the gas phase VOC concentration in ng/L divided by the liquid phase VOC concentration in μg/L.

The dosing compounds were contained in a 35 L Tedlar bag filled with 34 L of water and 1 L methanol (Figure 2.4). The methanol was used to promote solubility of the VOCs. A pure methanol solvent was not used because of the possibility of VOC precipitation when mixed with the wastewater. A measured quantity of each VOC was injected into the bag with a volumetric syringe to achieve the target influent concentration. The dose solution was pumped through 9.5 mm Viton tubing into the pilot plant influent line by a peristaltic pump. As the bag contents were emptied, the bag collapsed upon itself and eliminated headspace. The flowrates of the dose stream and the pilot plant influent stream were measured. A helical static mixer was placed in the pilot plant influent line to ensure total mixing of the VOC solution with the

Table 2.1a- Candidate VOCs and Target Influent Concentration (μg/L)

Non-Chlorinated Aromatics		Chlorinated Aliphatics	
Toluene	30	Dichloromethane	70
p-Xylene	30	Chloroform	25
4-Ethyl Toluene	20	1,1,1-Trichloroethane	10
1,3,5-Trimethylbenzene	30	Trichloroethylene	25
		Tetrachloroethylene	5
Chlorinated Aromatics			
1,4-Dichlorobenzene	15		

Table 2.1b- Summary of Candidate VOCs Physical Properties*

Compounds	M.W.	Henry's Law Constant (ng/L/μg/L)	Diffusion Coeff. (water) (cm^2/s)	Log Octanol-Water Partition Coefficient
Toluene	92.00	250	8.60E-06	2.7
p-Xylene	106.16	220	7.80E-06	3.2
4-Ethyl Toluene	120.20			
1,3,5-Trimethylbenzene	120.20			3.4
1,4 Dichlorobenzene	147.00	110	7.86E-06	3.4
Dichloromethane	85.00	130	1.17E-05	1.2
Chloroform	119.40	140	1.00E-05	2.0
1,1,1-Trichloroethane	133.40	200	8.80E-06	2.5
Trichloroethylene	131.39	380	9.10E-06	2.5
Tetrachloroethylene	165.90	1190	8.20E-06	2.5

*The first three data columns were obtained from the Phase I report. Octanol-water partition coefficients were obtained from a treatability database (US EPA, 1988).

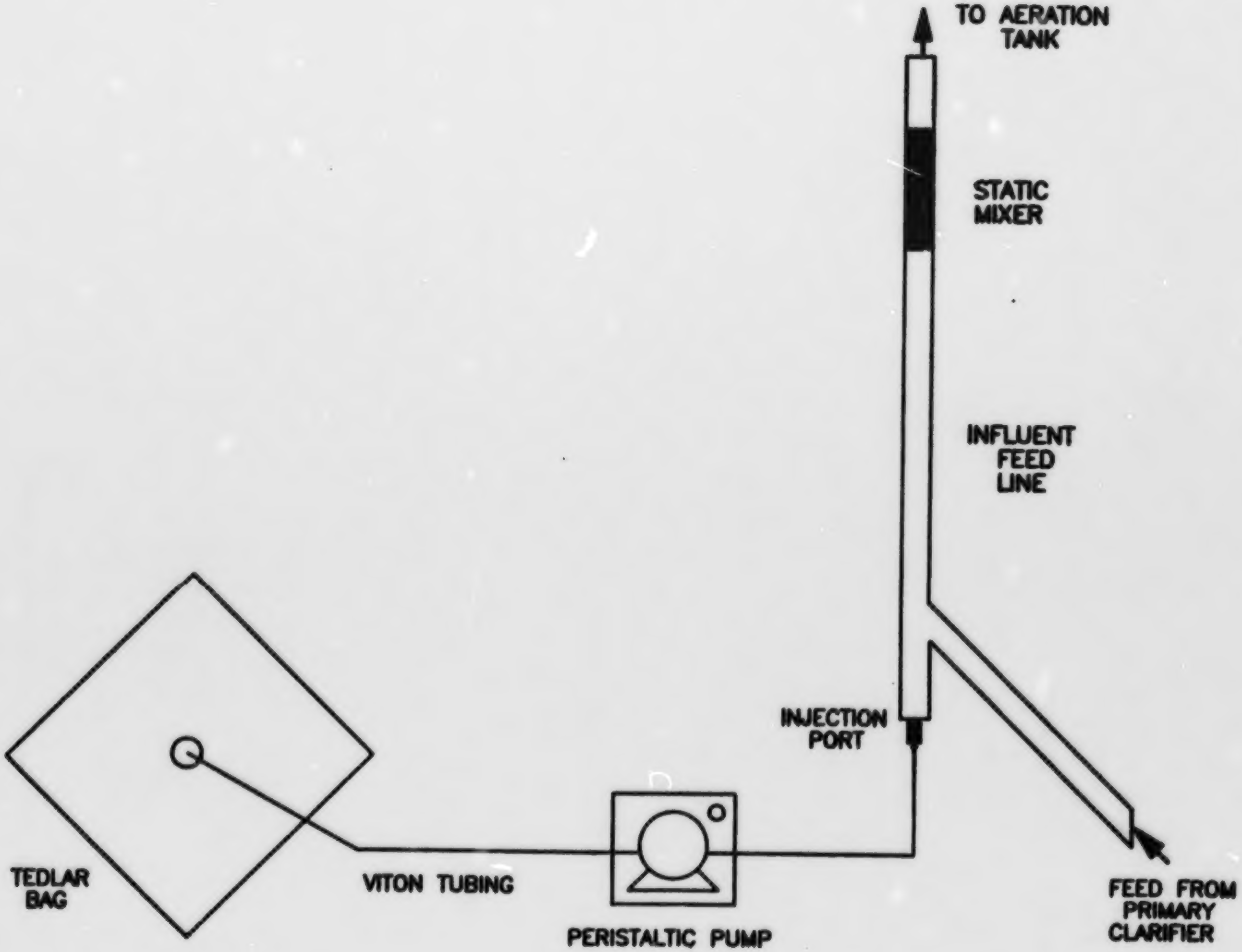

TO AERATION
TANK
STATIC
MIXER
INFLUENT
FEED
LINE
INJECTION
PORT
FEED FROM
PRIMARY
CLARIFIER
TEDLAR
BAG
VITON TUBING
PERISTALTIC PUMP

FIGURE 2.4 DOSING INJECTION APPARATUS

primary settler effluent.

Preparation of the dosing solution was initiated by pumping distilled water into the evacuated Tedlar bag through Viton tubing. Measured aliquots of five VOCs were then drawn into a 25 mL syringe partially filled with methanol. 1,4-dichlorobenzene is a room temperature and had to be dissolved in methanol. The syringe then pierced the Viton tubing and the solution was injected into the line as close to the Tedlar bag as possible. The flow of water carried the VOCs into the Tedlar bag. The procedure was then repeated for the remaining five VOCs. Finally, the Tedlar bag was gently stirred for 24 hours using a magnetic stir bar. A number of VOC droplets were visible after filling the bag, but these disappeared after 24 hours of stirring.

A sample port was provided in the Viton line leading from the Tedlar bag to the pilot plant influent line. Dosing solution samples were taken from this sample port at the beginning and end of the off-gas sampling interval for the first four dosed tap water (Phase II-A) experiments. Results from the dosing solution sampling are contained in Appendix B. There was significant variability in the dosing solution concentration measurements between experiments, but, for a given experiment, sample concentration measurements were consistent. Thus, it was concluded that, for a given experiment, the dose chemicals were entering the pilot plant influent line at an acceptably constant rate. Since dosing solution concentration measurements were not used for any experimental analysis, monitoring of the dosing solution concentration was discontinued.

2.4 Off-gas Sampling

2.4.1 Pilot Plant Off-gas Sampling

The pilot plant aeration basin and both settlers were covered and vented to the atmosphere. The vent stack above the aeration basin was dampered and the pressure monitored. A slight positive gauge pressure (< 2.5 cm water) was maintained to ensure that no ambient air leaked into the vent system. Aeration basin off-gas samples were drawn from the 10 cm diameter vent stack via a 6.4 mm diameter stainless steel sample line (Figure 2.5). The sample stream was passed through a Tenax adsorbent trap where the VOCs were collected. Duplicate samples were taken by splitting the sample stream and drawing it through parallel traps. In cool weather, the sample line and adsorbent traps were insulated and heated to 20 °C to protect against VOC condensation. The sample stream was drawn through the traps by the vacuum created by pumping water from a closed 5 L cylinder with a peristaltic pump. The volume of water pumped from the cylinder was measured at the end of each sampling experiment to determine the volume of gas drawn through the trap. The off-gas sample volume ranged from 0.5 to 4.0 L and was adjusted to ensure that the analytical calibration limit was not exceeded.

2.4.2 Full Scale Aeration Basin Off-gas Sampling

Off-gas samples from the full scale aeration basins were collected from 1.49 m^2 floating chambers secured by ropes in the aeration basins. The chambers floated on the wastewater surface with the skirt submerged. A slight positive gauge pressure (<2.5 cm water) in the sampling chamber prevented ambient air from leaking in. Each chamber had a 8 cm diameter vent stack 0.5 m above the liquid surface from which the off-gas was drawn. Before each sampling experiment, the sample line was purged by drawing fresh sample through the line with a vacuum pump. The remainder of the sampling procedure was very similar to that employed at the pilot plant and a full description is provided in the Phase I report, (Bell et al., 1988).

The sampling chambers were also used to measure the airflow

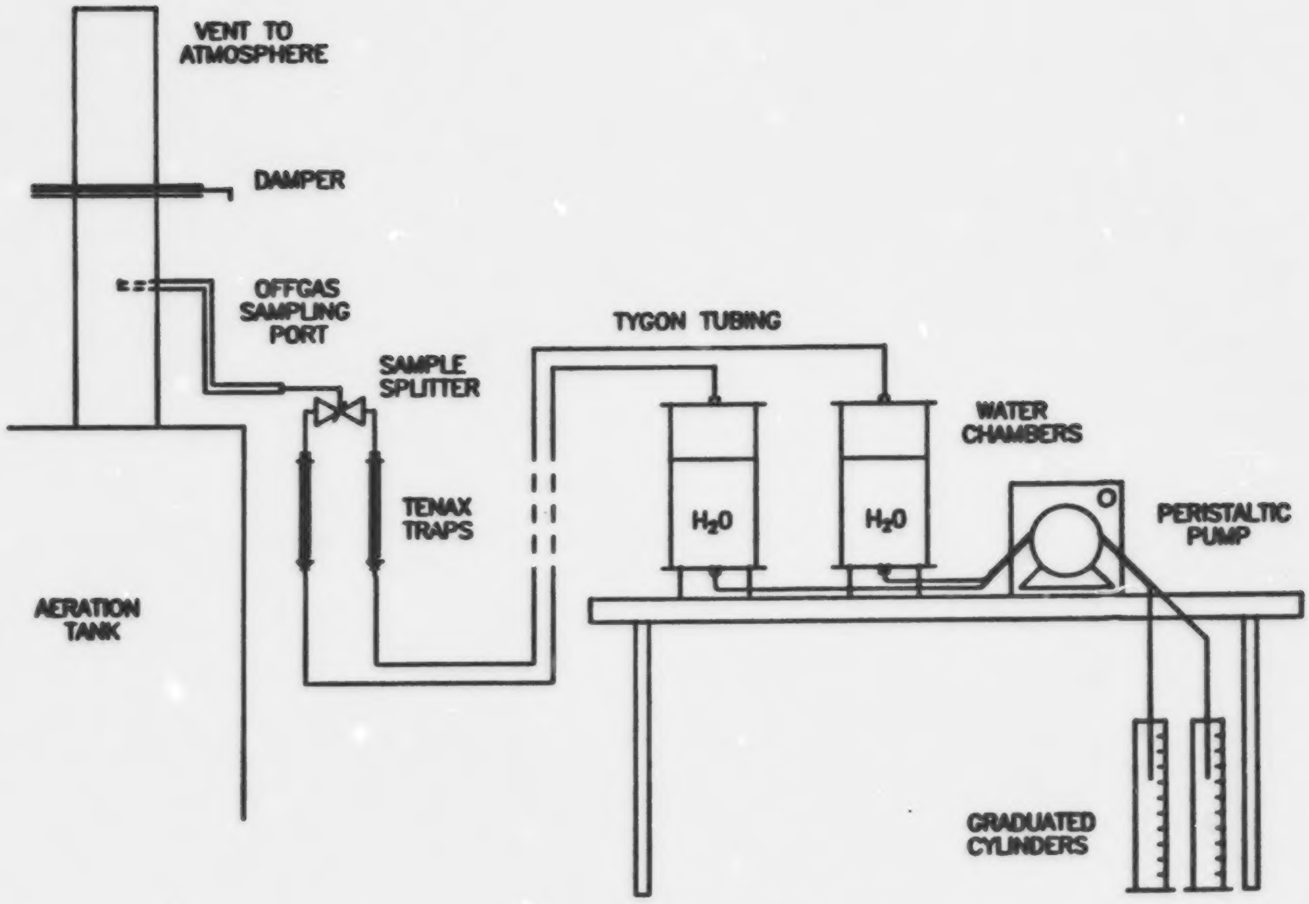

VENT TO
ATMOSPHERE
DAMPER
OFFGAS
SAMPLING
PORT
SAMPLE
SPLITTER
TENAX
TRAPS
AERATION
TANK
TYGON TUBING
H_2O
H_2O
WATER
CHAMBERS
PERISTALTIC
PUMP
GRADUATED
CYLINDERS

Figure 2.5 Off–Gas Sampling From Pilot Plant Ventilation Stack

rates at the sample location. During air flow measurements, the exit stack of the sampling chamber was connected to the inlet of a rotameter by a 5 cm diameter flexible hose. The outlet end of the rotameter was connected to the suction side of a portable vacuum cleaner. A flow control valve in the vacuum suction line was used to regulate the airflow from the sampling chamber. The interior of the sampling chamber was connected via 0.5 cm diameter flexible tubing to a Magnehelic differential pressure gauge. The gauge measured the pressure difference between the sampling chamber and the atmosphere. The airflow rate from the chamber was adjusted with the flow control valve until this pressure difference was within 0.2 cm of water of zero. At that point it was assumed that the headspace in the sampling chamber was at atmospheric pressure and the airflow rate was read from the rotameter and recorded.

2.5 Analysis of Off-gas Samples

2.5.1 Adsorbent Traps

The adsorbent traps consisted of stainless steel sampling cartridges packed with 60/80 mesh Tenax TA. The cartridges were 175 mm long and 15 mm wide with Swagelock 316 stainless steel end fittings and caps. Cartridges were packed with 3 g of Tenax which was prepared by overnight solvent extraction with methanol, followed by overnight solvent extraction with pentane. The Tenax was dried in a vacuum oven at 60°C for six hours and was sandwiched between plugs of silanized glass wool in the cartridges. The cartridges were conditioned overnight by passing 100 mL/min ultra-high purity helium through them at 220°C.

2.5.2 Off-gas Sample Analysis

The Tenax traps were analyzed for the presence of 37 VOCs on the MOE Effluent Monitoring Priority Pollutant List (Ontario Ministry of Environment, 1988). A statistically derived method detection limit was not reported, but the absolute detection limit was approximately 2 ng/sampling cartridge. Since the sample volumes ranged from 0.5 to 4.0 L the absolute detection limit ranged from 0.5 to 4 ng/L.

Analysis was performed with an automated thermal desorption system (Wang Consultants) interfaced with a Hewlett Packard (HP) 5890 gas chromatograph with an HP 5970 mass selective detector (MSD). Cartridges were purged with helium at 50 cc/min while being heated to 200°C during the desorption stage. Desorption time was 30 minutes. Volatiles were collected on a nickel trap maintained at -195°C with liquid nitrogen and filled with 60/80 mesh inert glass beads to increase trapping efficiency. A Perma Pure dryer (Perma Pure Inc., Farmingdale N.J.) prior to the cold trap removed moisture and polar organics from the sample stream. The trap was flash heated to 150°C delivering collected volatiles on to a 60 m DB-1 (0.32 mm ID, 1.0 micron film thickness) stationary phase column. Eluents were analyzed by MSD.

An instrument performance reference standard of n-alkanes (Supelco, cat no 2-3444) was run daily. A response deviation of greater than +/- 10% resulted in a full instrument recalibration. Fourteen calibrations were employed during the study period.

2.5.3 Off-gas Analysis Calibration

The off-gas analysis calibration procedure was independently examined during this study. Details of this investigation are contained in Appendix F. It was concluded that the calibration technique employed in this investigation under-estimated the VOC off-gas concentration, and a more appropriate calibration procedure was developed. Rather than revise the original calibration procedure part way through the investigation, a correction factor was applied to all off-gas data at the end of the investigation. A description of both calibration procedures and the correction procedure is provided below.

With both procedures the external standard calibration method was used. The calibration flask consisted of a 3 L spherical glass flask with dual sampling ports. The ports were designed such that teflon stopcocks located in-line between the flask body and septum assemblies maintained the chamber integrity during intervals between sampling. Approximately 10 µL of a neat gravimetric standard of the 37 VOCs was added to the clean nitrogen filled flask. The flask was sealed and heated to between 150 and 170°C. In the original calibration procedure, four hours were allowed for vaporization, mixing of the sample and thermal equilibrium, then aliquots of the gas were drawn from the hot bulb for injection into the GC/MSD. With the revised calibration procedure, the calibration flask was again heated to between 150 and 170 °C and four hours were allowed for vaporization, but the flask was allowed to cool to room temperature before aliquots of the gas were drawn off for injection into the GC/MSD. With both calibration procedures, a total of five injections were made with five different initial gravimetric standards, and a five level calibration was constructed for each compound.

To obtain the calibration correction factor, three pairs of calibrations were performed using the original and the revised technique. The two calibrations forming the pair were performed on the same day to ensure similar instrument performance. The calibration equations were of the form:

$$\text{amount}=(\text{response}/M)^{1/x} \quad \text{..........................} (2.1)$$

where:

amount=amount of compound (ng)
response=instrument response
M=constant
x=constant

For each calibration pair, the two calibration equations and the ratio of the revised technique equation to the original technique equation were plotted (Figure 2.6). This ratio was labelled the correction factor for that calibration pair. Thus, for each candidate VOC, a plot of correction factor versus instrument response was obtained for each calibration pair. Finally, for each candidate VOC, the three correction factor plots were averaged to obtain a single plot of correction factor versus instrument response.

To revise the off-gas concentration data analyzed using the original calibration technique, the appropriate calibration factor was selected from the correction factor plot using the original instrument response (Figure 2.6). The originally reported VOC amount was then multiplied by this correction factor. The correction factors generally ranged from 1.2 at high concentrations to 2.0 at low concentrations. Thus, all VOC concentration data analyzed using the original calibration technique were multiplied by a factor ranging between 1.2 and 2.0.

2.5.4 Off-gas Analysis Quality Assurance

An extensive off-gas analytical quality assurance program was presented in the Phase I report (Bell *et al.*, 1988). Throughout this Phase II study, blank traps containing clean Tenax were analyzed in the same manner as sample traps. For most compounds the blank concentrations were less than 1% of the sample concentrations. However, high concentrations of toluene, and to a much lesser extent dichloromethane, were observed for a period. The source of the high blank level was discovered to be an air leak in the laboratory thermal desorber which was contaminating the Tenax. All toluene off-gas data analyzed during this period were discarded. Approximately 75% of the off-gas samples were measured in duplicate, but the coefficients of variation for the duplicate

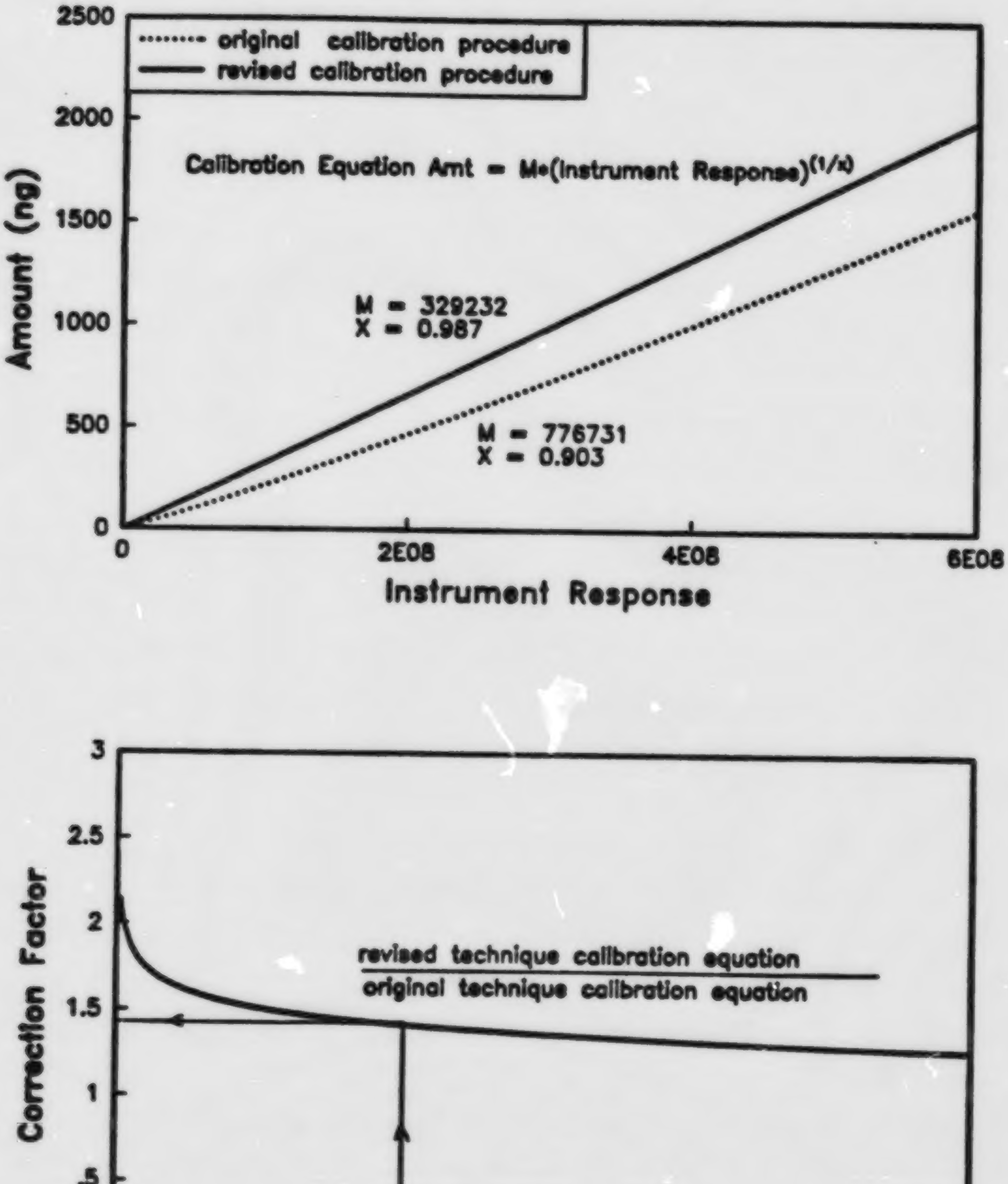


Figure 2.6—Example of Off—gas Calibration Correction Factor (Toluene)

tests were generally less than 20%, indicating good precision for the sampling and analytical methods. Four breakthrough tests were conducted by placing a second trap in series with, and downstream of, the primary trap. However, for all compounds, the concentration of VOCs on the second trap were less than 2% of the sample concentration.

2.6 Wastewater Sampling and Analysis

Wastewater samples were collected in 60 mL amber, septum top bottles. The samples were refrigerated at 4 °C during storage and transported to the analytical laboratory. Analysis was performed by three laboratories:

-Wastewater Technology Centre using purge and trap gas chromatography. A modified version of U.S. EPA method 624 was employed with 5 mL sample aliquots and a 30 m capillary chromatographic column. Electron capture and flame ionization detectors were both employed.

-Barringer Laboratories, Mississauga, Ontario using purge and trap gas chromatography/mass spectroscopy. A modified version of U.S. EPA method 624 was employed with 25 mL sample aliquots and a 60 m capillary chromatographic column. The mass spectrometer used was a Finnigan 1020 OWA with a 1050 software upgrade.

-Canviro Laboratories, Kitchener, Ontario using purge and trap gas chromatography/mass spectroscopy. A modified version of U.S. EPA method 624 employed with 5 mL sample aliquots and a 60 m capillary chromatographic column. The mass spectrometer used was an HP 5970).

The WTC laboratory, which did not use an MSD, was employed only during dosed tap water and wastewater experiments where chromatographic identification was possible. The statistically determined method detection limits (MDL) for each compound were different for each laboratory but were generally below 2 µg/L. Occasionally, compounds were reported at levels below the MDL but above the instrument detection level. These values were used for experimental analysis but are reported with an asterisk in the raw data appendices. All three laboratories used analysis duplicates, laboratory blanks and surrogates for quality assurance/quality control (QA/QC). Surrogate recovery data were used to monitor analytical performance but were not used to adjust any reported data. The surrogate recovery data are reported in Appendix C.

2.7 Gas-Liquid Phase Mass Transfer Tests

Matter-Muller et al., (1981) presented an expression for predicting the relationship between gas-phase VOC concentration and liquid phase VOC concentration in a diffused aeration system. They recognized a limitation in the Henry's Law description of saturation in aerated wastewater applications by introducing a fractional saturation term in their relationship. They defined fractional saturation as the ratio of the measured off-gas concentration to the saturation off-gas concentration predicted by Henry's Law. Fractional saturation is predicted by,

$$f = 1-\exp(-K_L aV/HQ_g) \quad \text{..........................} \quad (2.2)$$

where:

f = fractional saturation,
$K_L a$= stripping mass transfer coefficient, (hr^{-1}),
H = dimensionless Henry's Law Constant,
V = aeration tank volume, (m^3), and
Q_g= airflow rate (m^3/hr).

In this work it was recognized that similarity needed to be established between the stripping process in the pilot plant and in a full scale aeration basin. To this end, it is known that stripping mass transfer coefficients can be estimated from oxygen mass transfer coefficients using film theory which states that mass transfer coefficients are directly proportional to diffusion coefficients. This suggests that an increase in the dimensionless term, oxygen K_LaV/Q_g, as defined in Equation 2.2, would increase the ratio of the gas phase to liquid phase concentration of the VOC until the gas bubble is saturated with the VOC. Accordingly oxygen K_LaV/Q_g was used to provide a basis for stripping process similarity between the pilot plant and the full scale aeration basin.

Oxygen mass transfer tests were performed on the pilot plant and in aeration basins at the Burlington Skyway WPCP and Toronto Highland Creek WPCP. Because coarse bubble diffusers were used at the Burlington Skyway WPCP and fine bubble diffusers at the Toronto Highland Creek WPCP, the two plants represented a range of typical full scale oxygen mass transfer conditions.

2.7.1 Pilot Plant Tap Water Tests

Pilot plant oxygen mass transfer tests in tap water were performed using ASCE standard procedures (Boyle et al, 1983). Sodium sulphite (Na_2SO_3) with a cobalt chloride catalyst was used as the deoxygenation chemical. Dissolved oxygen (DO) concentration was monitored using Yellow Spring Instruments DO meters. The increase in DO concentration after deoxygenation was related to a mass transfer coefficient (K_La) using the equation:

$$\frac{dDO(t)}{dt} = K_La(DO_{sat}-DO(t)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

where:
$DO(t)$= dissolved oxygen concentration at time t, (mg/L),
K_La = oxygen mass transfer coefficient, (hr^{-1}),
DO_{sat}= saturation dissolved oxygen concentration, (mg/L),

The measured K_La was adjusted to standard conditions (20°C). Sample calculations of the tap water K_La are presented in Appendix G.

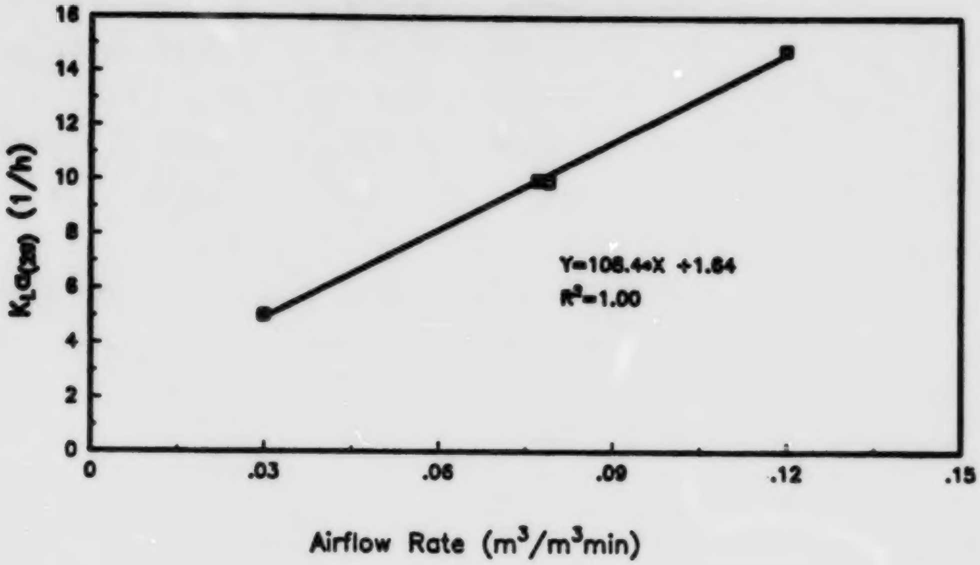
Four tests were performed with the coarse bubble diffuser system at air flowrates ranging from 0.03 to 0.12 m^3/m^3min. Six tests were performed with the fine bubble diffuser system at air flowrates ranging from 0.015 to 0.052 m^3/m^3min. Figure 2.7 summarizes the relationship between K_La and airflow for the two diffusers systems. Both diffuser systems performed closely to manufacturer predictions. With the fine bubble diffuser system the oxygen K_LaV/Q_g was approximately 4.5 and was approximately 2.2 with the coarse bubble diffuser system.

2.7.2 Pilot Plant Tests, Process Water

Process water oxygen transfer efficiency is generally lower than tap water oxygen transfer efficiency because of the presence of surfactants and solids in the mixed liquor. Process water mass transfer coefficients are frequently expressed as αK_La. The alpha factor, α, measures the ratio of the process water oxygen transfer efficiency to the tap water oxygen transfer efficiency. Because alpha, α, varies with wastewater source and diffuser type, pilot plant process water oxygen mass transfer coefficients, αK_La, were measured at the Burlington site and the Toronto Highland Creek site.

Pilot plant process water oxygen mass transfer tests were made using the off-gas technique outlined by Redmon et al. (1983). The off-gas analyzer was an Aerator-Rator of Ewing Engineering Company, Milwaukee, Wisconsin. A portion of the off-gas leaving the pilot plant vent stack was diverted to the off-gas analyzer where the oxygen concentration was measured. By comparing the off-gas concentration in the plant influent air to the off-gas concentration of the air leaving the aeration basin and measuring the dissolved oxygen concentration in the aeration basin, process water mass transfer coefficients (αK_La) were derived. Sample

Coarse Bubble Diffuser



Fine Bubble Diffuser

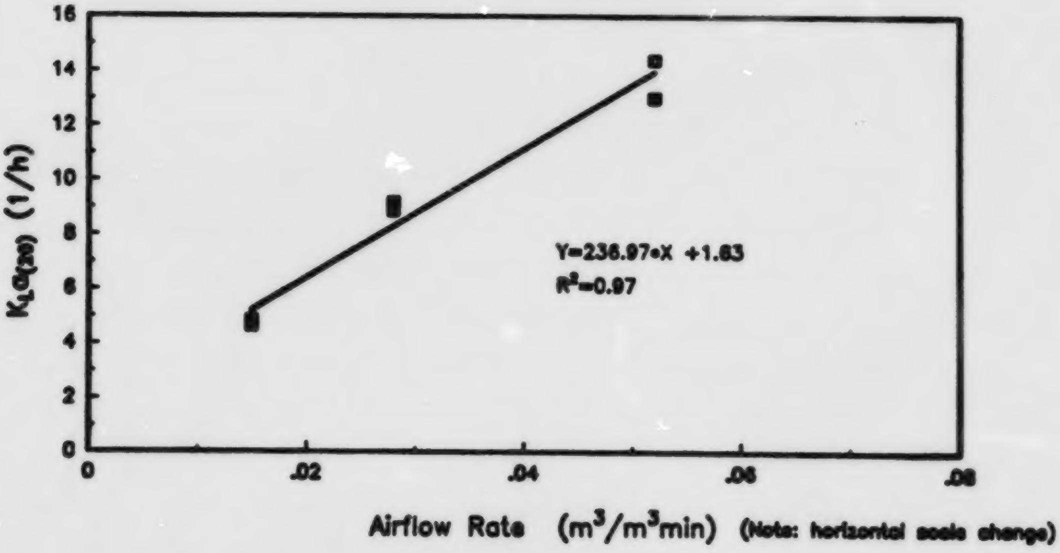


Figure 2.7 Pilot Plant Clean Water K_La vs. Airflow Rate

calculations are presented in Appendix G.

Many process water oxygen mass transfer coefficient tests were performed at different air flowrates and Figures 2.8a and 2.8b summarize the results for Burlington Skyway WPCP wastewater and Toronto Highland Creek WPCP wastewater at a 5 day SRT. With Burlington Skyway WPCP wastewater and a SRT of 5 days, the pilot plant oxygen $\alpha K_L aV/Q_g$ ranged from 1.02 to 1.13 with the coarse bubble diffusers and from 1.22 to 1.29 with the fine bubble diffusers. With Toronto Highland Creek WPCP wastewater and a SRT of five days, the pilot plant oxygen $\alpha K_L aV/Q_g$ was 1.1 with the coarse bubble diffusers and ranged from 2.0 to 2.3 with the fine bubble diffusers.

2.7.3 Full Scale Tests

The off-gas analyzer described in Section 2.7.2 was used for measuring full scale oxygen mass transfer coefficients. A brief description of the experimental procedure is described below and details are provided in Appendix G.

Burlington Skyway WPCP

The Burlington Skyway WPCP aeration basin was 80 m long by 8 m wide and consisted of 9 coarse bubble diffuser laterals. Airflow measurements taken across the width of the aeration basin showed that the airflow was reasonably uniform along the cross section. The diffuser laterals divided the aeration basin into 10 geometric cells. Three of these cells were sampled using a 2.4 m by 1.2 m sampling hood. For each cell, the hood was placed lengthwise so that its leading edge was directly over the center of the diffuser lateral (Figure 2.9a). The hood was then placed sideways between the diffuser laterals. Finally the hood was placed so that the trailing edge was directly over the second diffuser lateral. In

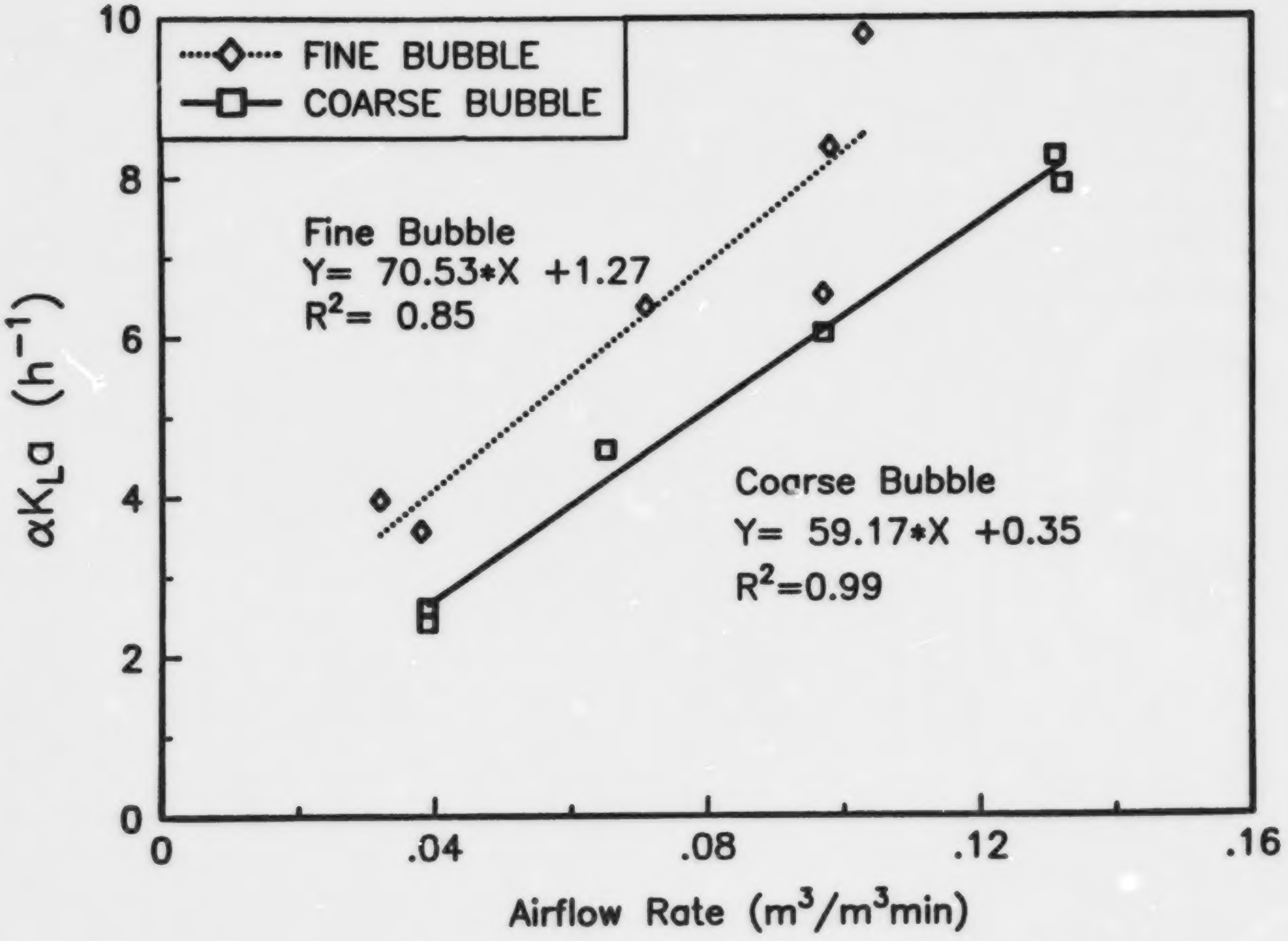


Figure 2.8a– Pilot Plant Process Water $\alpha K_L a$ vs. Airflow Rate (Burlington Skyway Wastewater)

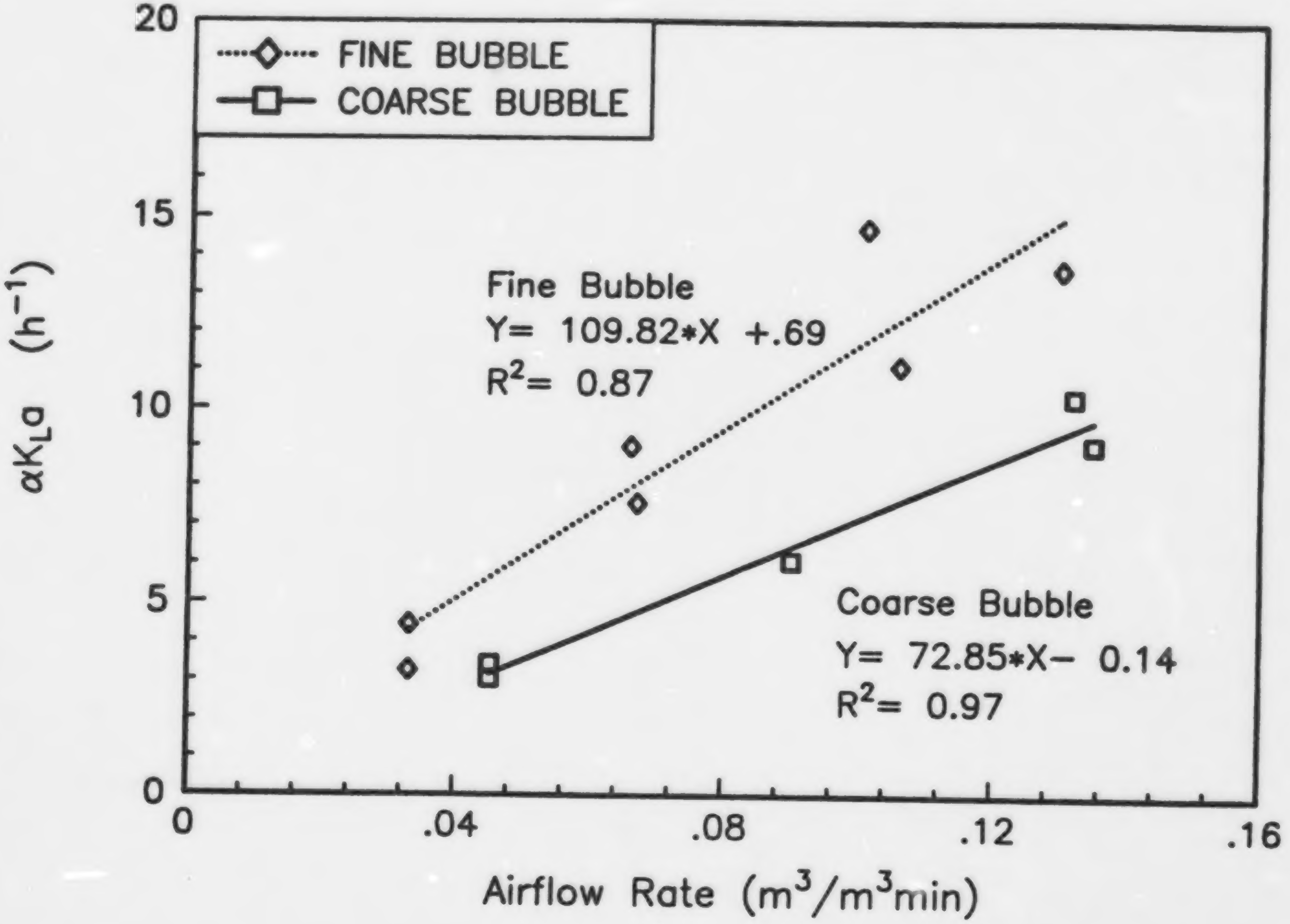


Figure 2.8b– Pilot Plant Process Water αK_La vs. Airflow Rate (Highland Creek Wastewater)

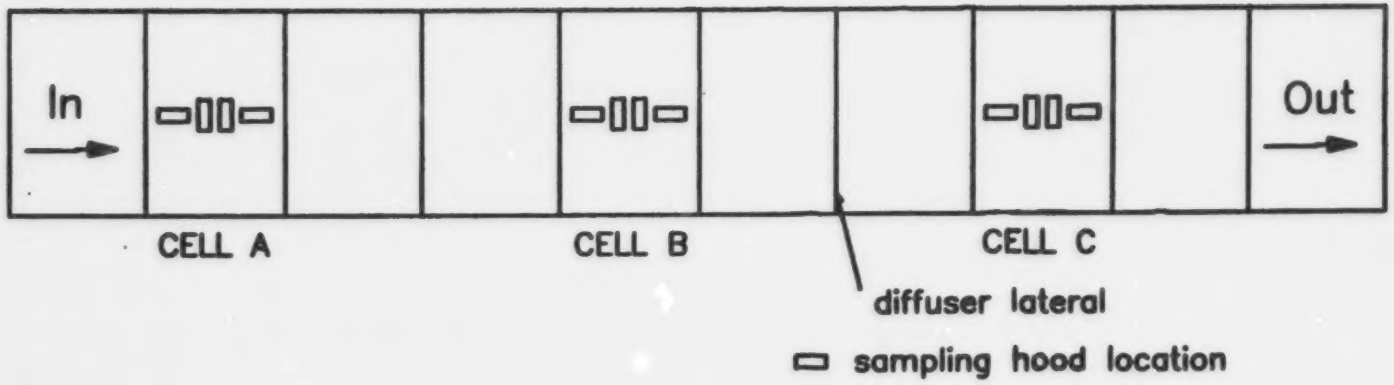

In
Out
CELL A
CELL B
CELL C
diffuser lateral
▭ sampling hood location

Figure 2.9a— Oxygen Off—gas Sampling At Burlington Skyway Aeration Basin

this way, each cell was subdivided into four cross sections each represented by a hood location. The off-gas DO concentration leaving the sampling hood, the airflow rate through the hood and the mixed liquor dissolved oxygen concentration were recorded at each hood location. The average cell oxygen αK_La's were determined by weight averaging the four hood location αK_La's based on the airflow rate of the cross section represented by the sampling hood. The average aeration basin oxygen αK_La was determined by weight averaging the three cell αK_La's based on the relative airflow per cell. The average aeration basin oxygen αK_La was calculated to be 2.1 hr^{-1} and the average $\alpha K_LaV/Q_g$ was 1.3.

To better determine the airflow rate pattern within an individual cell, a single cell was sampled by placing the 1.49 m^2 sampling chambers directly over a diffuser lateral, 1/4 of the way between diffuser laterals and half way between diffuser laterals (Figure 2.9b). The airflow rates through the sampling chambers over each location were 0.7, 0.06 and 0.02 m^3/min respectively, indicating that the majority of the air leaving the aeration basin left directly over the diffuser laterals. The oxygen $\alpha K_LaV/Q_g$ directly over the diffuser lateral was 0.9, and was 8.1 at a distance 1/4 of the way between the diffuser laterals. Mid-way between the diffuser laterals, the oxygen $\alpha K_LaV/Q_g$ approached infinity because of the low airflow rate. An average basin oxygen αK_La was determined by weight averaging the two measured αK_La's based on relative airflow rate. The average basin oxygen $\alpha K_LaV/Q_g$ was 1.4, consistent with the previous result.

Toronto Highland Creek WPCP

The Toronto Highland Creek WPCP aeration basin was 36 m long by 8.8 m wide and contained a uniform distribution of fine bubble

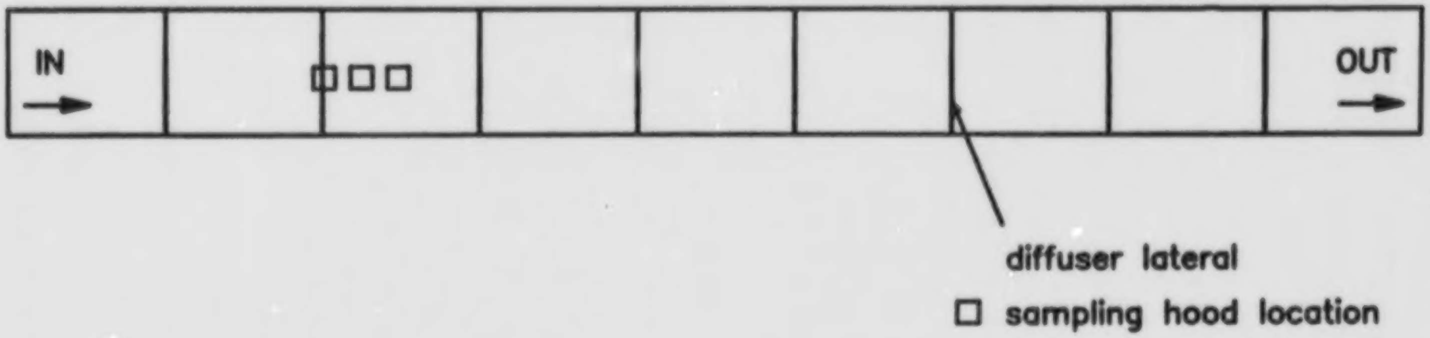

IN
OUT
diffuser lateral
□ sampling hood location

Figure 2.9b– Oxygen Offgas Sampling at Burlington Skyway Aeration Basin (Method B)

dome diffusers. A 1.2 m by 2.4 m sampling hood was placed in seven locations along the length of the aeration basin, and the off-gas concentration leaving the sampling hood, the airflow rate leaving the hood and the dissolved oxygen concentration were recorded at each hood location. The airflow rate and the oxygen mass transfer coefficients were reasonably constant at each location. The average aeration basin oxygen mass transfer coefficient was determined by weight averaging the seven measured αK_La's based on the relative airflow rates. The average oxygen αK_La was determined to be 4.08 hr^{-1} and the average oxygen $\alpha K_LaV/Q_g$ was 3.51.

2.7.4 Oxygen Mass Transfer Testing Summary

Results from the oxygen mass transfer testing are summarized in Table 2.2. The pilot plant aeration basin was not as deep as the full scale aeration basins, and when filled with mixed liquor, the pilot plant could not achieve the oxygen $\alpha K_LaV/Q_g$ of the Toronto Highland Creek WPCP aeration basin but could achieve it when filled with tap water. Since dosed tap water experiments were employed, the pilot plant was able to span a typical range of full scale aeration basin oxygen mass transfer conditions.

2.8 Hydraulic Characterization

The hydraulic characteristics of the aeration basins were required to establish the stripping conditions and to understand VOC off-gas concentration data. Thus the hydraulic characteristics of the pilot plant and the Toronto Highland Creek WPCP and Burlington Skyway WPCP full scale aeration basins were examined using a Rhodamine dye procedure. Rhodamine concentrations were determined using a Turner fluorometer and an empirically determined calibration curve. A mathematical model describing the washout curve from a theoretical continuous stirred tank reactor (CSTR) or

Table 2.2-Summary of Oxygen Mass Transfer Tests

Pilot Plant:

	Tap Water K_LaV/Q_g	Burl. Skyway Process Water $\alpha K_LaV/Q_g$	Highland Cr. Process Water $\alpha K_LaV/Q_g$
Fine Bubble	4.5	1.2	2.2
Coarse Bubble	2.2	1.1	1.1

Full Scale Aeration Basins:

	Process Water $\alpha K_LaV/Q_g$
Toronto, Highland Creek WPCP	3.5
Burlington Skyway WPCP	1.3

from a number of CSTR's in series (Randle et al., 1988) was used to analyze the data. The inputs to the model were the nominal HRT and the initial dye concentration. A brief description of the experimental procedure and a summary of results are provided below.

2.8.1 Pilot Plant Hydraulic Characterization

Before injecting the dye, the pilot plant recycle flow (5 L/min) was turned off and the influent flowrate increased from 13.5 to 18.5 L/min (HRT of 4.6 hours). The coarse bubble diffuser system was employed and the air flowrate was adjusted to a moderate 0.28 m^3/min. A syringe was used to inject Rhodamine into the pilot plant primary effluent line. Mixed liquor samples were taken every five minutes from the line leading from the aeration basin to the secondary settler.

Figure 2.10 compares the observed pilot plant aeration basin effluent dye concentration to the dye concentration from a CSTR with an HRT of 4.6 hours. The observed data match the model prediction, and it was concluded that the contents of the pilot plant were completely mixed at all air flowrates employed during the study. This implies that the aeration basin effluent VOC concentration represented the VOC concentration in the aeration basin. It was assumed that volatilization in a covered secondary settler is minimal, and the secondary settler effluent VOC concentration represented the VOC concentration in the aeration basin.

2.8.2 Hydraulic Characterization, Toronto Highland Creek WPCP

At the Toronto Highland Creek WPCP, the Rhodamine was injected into the head end of the aeration basin and sampling of the mixed liquor leaving the aeration basin was begun immediately. The

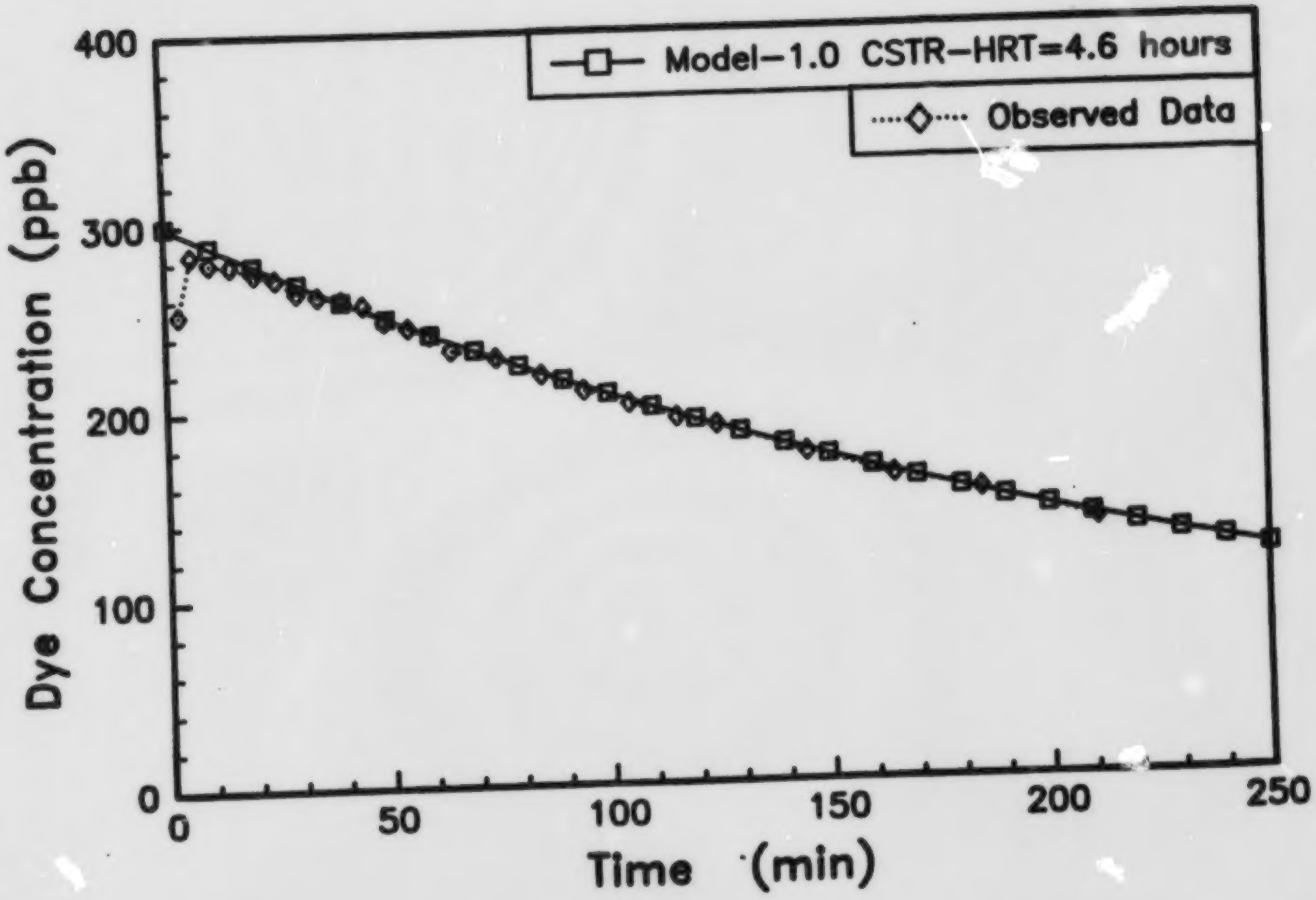


Figure 2.10 Pilot Plant Aeration Basin Washout Curve

return activated sludge (RAS) flow could not be turned off, but the RAS flow from eight of the plant's secondary settlers fed into a common channel and was distributed among eight aeration basins. Thus, the Rhodamine concentration in the RAS was diluted and the confounding effect minimized.

Determining an accurate nominal HRT of the aeration basin was difficult. There was a flowrate measurement on the inflow to eight primary settlers feeding eight aeration basins, but the flow distribution between aeration basins was visibly uneven and there was no measurement of the RAS flows. Plant operators estimated a total HRT of the sampled basin between 3 and 5 hours.

The observed washout curve from the Toronto Highland Creek WPCP aeration basin is shown in Figure 2.11. The peak effluent dye concentration was observed 45 minutes after the dye was injected into the basin. However, after the peak concentration, the washout curve is very similar to a CSTR washout curve indicating strong complete mix characteristics. A number of model expressions were superimposed over the data, and a fit of 1.05 CSTRs in series (i.e. a small tank feeding a much larger tank) with a total HRT of 5 hours was judged by visual inspection to best fit the data. Thus, minimal variation in VOC concentration was expected along the length of the Toronto Highland Creek WPCP aeration basin.

2.8.3 Hydraulic Characterization, Burlington Skyway WPCP

For the Burlington Skyway WPCP, the Rhodamine was injected into the head end of the aeration basin and sampling of the mixed liquor leaving the aeration basin was begun immediately. The return activated sludge (RAS) flow could not be turned off, but the RAS flow from all of the plant's secondary settlers fed into a common channel and was distributed among six aeration basins.

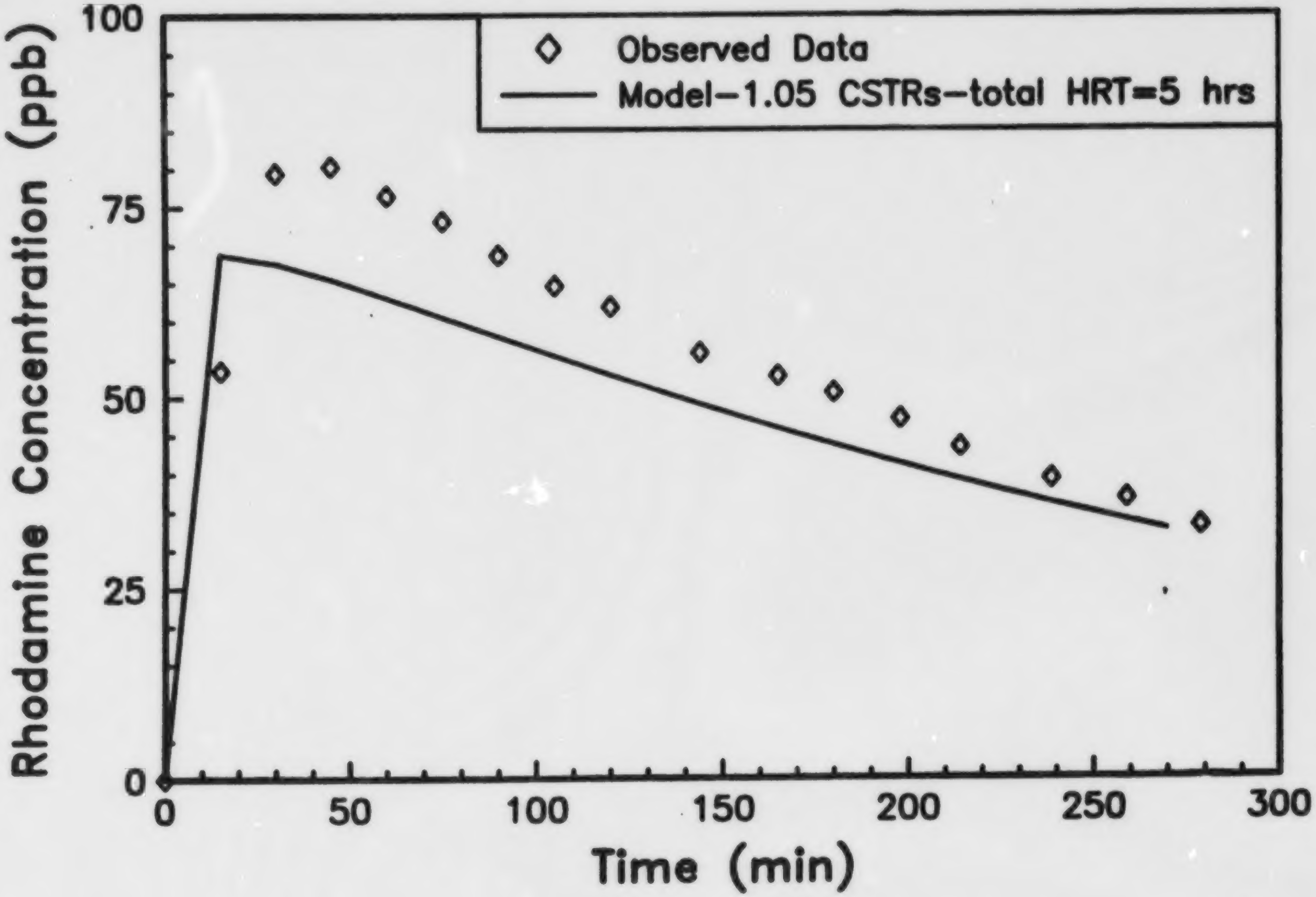


Figure 2.11 Highland Creek Full Scale Aeration Basin Washout Curve

Thus, the Rhodamine concentration in the RAS was diluted and the confounding effect minimized.

Determining an accurate nominal hydraulic residence time of the aeration basin was difficult. There was a flowrate measurement on the inflow to six aeration basins, but the flow distribution between aeration basins was visibly uneven and there was no measurement of the RAS flows. The flow through the Burlington Skyway WPCP was high throughout the study period because of backwash from the potable water plant, and plant operators estimated a total HRT between 3 and 5 hours.

The observed washout curve from the Burlington Skyway WPCP aeration basin is shown in Figure 2.12. The peak dye concentration was observed 70 minutes after the dye was injected into the basin indicating that the basin was not completely mixed. A number of model expressions were superimposed over the data, and a fit of 1.3 tanks in series with a total HRT of 3.0 hours was judged by visual inspection to best fit the data. Thus, more spatial variation in VOC concentration was expected along the length of the Burlington Skyway WPCP aeration basin than along the Toronto Highland Creek WPCP aeration basin.

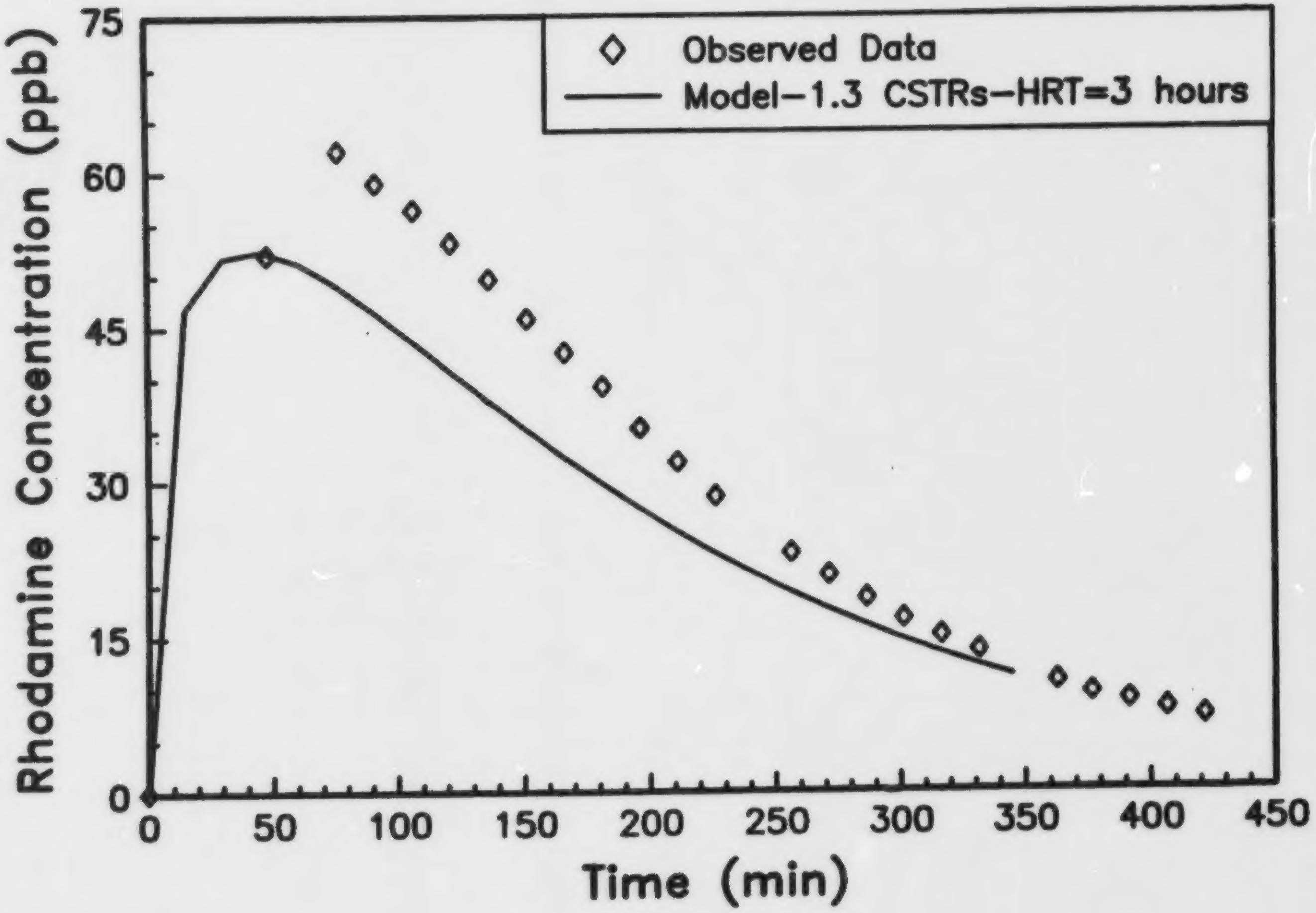


Figure 2.12 Burlington Skyway Full Scale Aeration Basin Washout Curve

3.0 RESULTS

3.1 Conventional Operating Parameters

3.1.1 Plant Design and Operating Data

Table 3.1a summarizes plant design and operation parameters for the Toronto Highland Creek and Burlington Skyway WPCPs. Table 3.1b summarizes pilot plant design and operation data. For the pilot plant the influent flowrate was constant at 13.5 L/min resulting in a nominal HRT of 6.2 hours. Airflow rate was varied for experimental purposes within a range of 0.02 and 0.16 m^3/m^3min (airflow rate per unit of reactor volume). These air flowrates satisfied the Ontario Ministry of Environment guidelines for mixing requirements of 0.02 m^3/m^3min (airflow rate per unit of reactor volume) for coarse bubble aeration systems and 0.04 m^3/m^2s (airflow rate per unit surface area of reactor) (Ontario Ministry of The Environment, 1988c). The pilot plant mixed liquor dissolved oxygen concentration was maintained above 1 mg/L at all times.

3.1.2 Conventional Treatment Data Collected From The Full Scale Water Pollution Control Plants

Conventional treatment data were collected from both the Burlington Skyway and Toronto Highland Creek WPCPs to ensure that pilot plant or full scale experiments were not conducted during a plant upset period. Appendix E contains the full scale conventional treatment data collected during the study period, and mean values of the data are presented in Tables 3.2a and 3.2b. The mean MLSS concentrations at the Burlington Skyway and Toronto Highland Creek WPCPs were 3.9 and 3.5 g/L respectively. The wasting schedules were irregular at both plants and no estimate of SRT was made. Under normal conditions, effluent suspended solids and BOD_5 concentrations were below 15 mg/L at both plants. At the Burlington Skyway WPCP, very high effluent suspended solids

Table 3.1a-Full Scale Plants Operating and Design Data

PARAMETER	Burlington Skyway	Toronto Highland Creek[1]
Aeration Basins		
Number	6	8
Dimensions, (WXLXD), m	8X80X5	17.6X36X4.6
Volume, m^3/basin	3200	2986
*Air Flowrate, m^3/min	853	238
Diffuser Type	Coarse	Fine
Air Flow Pattern	Cross Roll	Uniform
*Average Wastewater Flow Rate During Sampling Period, m^3/d	96,000	80,000
*Hydraulic Residence Time, h	4.8	6.8
*Aeration Rate, m^3air/m^3water	16	4.4

[1] old plant only

*- based on full scale plant instrumentation

Table 3.1b-Pilot Plant Operating and Design Data

Aeration Basin Volume, m^3	5
Range of Air Flowrates, m^3/m^3min	0.02-0.16
Influent Flowrate, m^3/d	19
Hydraulic Residence Time, h	6.2

Table 3.2a- Conventional Operating Data Collected From Burlington Skyway WPCP During Study Period

	MLSS	Aeration Basin Influent			Secondary Settler Effluent			
	Conc. (g/L)	BOD_5 Conc. (mg/L)	TKN Conc. (mg/L)	Total P (mg/L)	Susp Solids Conc. (mg/L)	BOD_5 Conc. (mg/L)	NH_3 Conc. (mg/L)	Total P Conc. (mg/L)
Avg*	3.9	133	23.5	4.7	10.0	9.2	0.28	2.0
Std Dev	0.5	15	1.5	0.4	3.7	2.9	0.08	0.3

*- average of all grab samples taken during study period

Table 3.2b- Conventional Operating Data Collected From Toronto Highland Creek WPCP During Study Period

	MLSS	Aeration Basin Influent			Secondary Settler Effluent			
	Conc. (g/L)	BOD_5 Conc. (mg/L)	TKN Conc. (mg/L)	Total P (mg/L)	Susp Solids Conc. (mg/L)	BOD_5 Conc. (mg/L)	NH_3 Conc. (mg/L)	Total P Conc. (mg/L)
Avg*	3.5	147	55.3	6.6	13.2	6.8	11.0	1.62
Std Dev	0.3	19	3.5	2.0	2.1	1.5	9.9	0.53

*- average of all grab samples taken during study period.

concentrations were observed during hydraulic surges caused by backwash from the municipal potable water plant. The high effluent suspended solids concentrations observed during these peak flows were not included in Table 3.2a. Essentially complete nitrification was achieved at the Burlington Skyway WPCP. Nitrification was achieved in September at the Highland Creek WPCP, but was not achieved in October resulting in the moderately high NH_3 concentration and the high variance presented in Table 3.2b.

Tables 3.3a and 3.3b summarize historical conventional treatment data for the Burlington Skyway and Toronto Highland Creek WPCPs collected during the summer of 1987 (Ontario Ministry of the Environment, 1988b). Most likely, influent BOD_5, TKN and phosphorus concentrations measured during the study period (Tables 3.2a and 3.2b) were lower than those measured during the historical period (Tables 3.3a and 3.3b) because, during the historical period, these measurements were taken before the primary settler and during the study period these measurements were taken following the primary settlers. Effluent suspended solids concentration data collected during the study period (Tables 3.2a and 3.2b) were very similar to data collected during the historical period (Tables 3.3a and 3.3b). Effluent phosphorus concentrations were slightly higher during the study period (Tables 3.2a and 3.2b) than during the historical period while nitrification was not achieved during the historical period at either plant (Tables 3.3a and 3.3b). These differences in performance are likely due to the normal variability in performance that water pollution control plants are subject to, and it was concluded that the Burlington Skyway and Toronto Highland Creek WPCPs were achieving normal conventional treatment efficiency during the study period.

Table 3.3a- Historical Conventional Operating Data; Burlington Skyway WPCP

	Influent Concentration			Effluent Concentration			
	BOD_5 (mg/L)	TKN (mg/L)	Total P (mg/L)	BOD_5 (mg/L)	Susp Solids (mg/L)	NH_3 (mg/L)	Total P (mg/L)
Avg	193	19	5	10	15	21	1
Std Dev	78	6	2	5	7	4	1

-data collected over a 15 day period, June 1987.

.Table 3.3b- Historical Conventional Operating Data; Highland Creek WPCP

	Influent Concentration			Effluent Concentration			
	BOD_5 (mg/L)	TKN (mg/L)	Total P (mg/L)	BOD_5	Susp Solids (mg/L)	NH_3 (mg/L)	Total P (mg/L)
Avg	176	29	5	7	12	18	1
Std Dev	28	2	1	5	2	2	< 1

-data collected over a 15 day period, July 1987.

3.1.3 Pilot Plant Conventional Treatment Data

Conventional treatment data collected from the pilot plant during each experimental phase and are presented in Appendix E. Mean values of the data collected when the plant was operated using Burlington Skyway wastewater at 5 and 10 day SRTs are presented in Tables 3.4a and 3.4b. The mean MLSS concentration of the pilot plant was 2.2 g/L at a 5 day SRT and 3.3 g/L at a 10 day SRT. The mean effluent suspended solids concentrations were below 20 mg/L and the effluent BOD$_5$ concentrations were below 15 mg/L at both SRTs. The effluent suspended solids contributed most of the BOD$_5$ because filtered effluent BOD$_5$ concentrations were consistently below 5 mg/L at both SRTs. Thus, plant performance was not affected substantially by the increase in SRT from 5 to 10 days.

A comparison of pilot plant conventional treatment efficiency to Burlington Skyway WPCP efficiency during the study period can be made by comparing Tables 3.4a and 3.4b to Table 3.2a. Pilot plant effluent suspended solids concentrations, and thus BOD$_5$ and phosphorus concentrations, were slightly higher than those observed at the Burlington Skyway WPCP. The higher effluent suspended solids concentrations were likely due to the shallowness of the pilot plant settler. Both the pilot plant and the full scale plant achieved nitrification throughout the study period. Thus, except for the slightly higher effluent suspended solids concentrations, the pilot plant matched the treatment efficiency of the Burlington Skyway WPCP.

Table 3.5 presents mean values of the pilot plant conventional treatment data collected when the pilot plant was operated using Highland Creek wastewater at a 5 day SRT. The mean MLSS concentration of the pilot plant was 3.3 g/L. The larger value of MLSS concentration achieved when the pilot plant was operated using Toronto Highland Creek wastewater, rather than Burlington Skyway wastewater (Table 3.4a), may be partially attributed to a higher

Table 3.4a- Conventional Operating Data Collected From Pilot Plant During Study Period (Burlington Skyway Wastewater; 5 day SRT)

	MLSS	Aeration Basin Influent			Secondary Settler Effluent			
	Conc. (g/L)	BOD$_5$ Conc. (mg/L)	TKN Conc. (mg/L)	Total P Conc. (mg/L)	Susp Solids Conc. (mg/L)	BOD$_5$ Conc. (mg/L)	NH$_3$ Conc. (mg/L)	Total P Conc. (mg/L)
Avg*	2.2	119	20.1	5.2	17	12	1.3	3.3
Std Dev	0.2	23	4.8	1.0	17	11	3.1	0.8

* -average of all grab samples collected during study period.

Table 3.4b- Conventional Operating Data Collected From Pilot Plant During Study Period (Burlington Skyway Wastewater; 10 day SRT)

	MLSS	Aeration Basin Influent			Secondary Settler Effluent			
	Conc. (g/L)	BOD$_5$ Conc. (mg/L)	TKN Conc. (mg/L)	Total P Conc. (mg/L)	Susp Solids Conc. (mg/L)	BOD$_5$ Conc. (mg/L)	NH$_3$ Conc. (mg/L)	Total P Conc. (mg/L)
Avg*	3.3	116	24.1	5.5	19.3	13	0.2	2.9
Std Dev	0.4	32	7.4	2.3	6.1	13	0.2	3.0

* -average of all grab samples collected during study period.

Table 3.5- Conventional Operating Data Collected From Pilot Plant During Study Period (Highland Creek WPCP; 5 day SRT)

	MLSS	Aeration Basin Influent			Secondary Settler Effluent			
	Conc. (g/L)	BOD_5 Conc. (mg/L)	TKN Conc. (mg/L)	Total P Conc. (mg/L)	Susp Solids Conc. (mg/L)	BOD_5 Conc. (mg/L)	NH_3 Conc. (mg/L)	Total P Conc. (mg/L)
Avg*	3.3	131	53.1	6.2	23.4	10	12.2	2.1
Std Dev	0.4	5	5.7	2.0	4.7	9	3.8	0.9

*- average of all grab samples collected during study period

influent organic load. At Toronto Highland Creek, effluent suspended solids concentrations were generally below 25 mg/L although occasional upsets were observed. Effluent BOD_5 concentrations were generally below 15 mg/L, and the majority of the BOD_5 was contributed by effluent solids. A comparison of pilot plant treatment efficiency to the Toronto Highland Creek WPCP treatment efficiency during the study period can be made by comparing Table 3.5 to Table 3.2b. Once again, pilot plant effluent suspended solids, BOD_5 and phosphorus concentrations were slightly higher than those observed at the full scale plant presumably because of the shallower pilot plant settler. Nitrification was achieved in September, but not October, in both the pilot plant and the full scale plant. Thus, except for the slightly higher effluent suspended solids concentrations, the pilot plant matched the treatment efficiency of the Toronto Highland Creek WPCP.

3.2 Pilot Plant Dosed Tap Water Experiments (Phase II-A)

Eight pilot plant dosed tap water experiments were completed. The experimental conditions are summarized in Table 3.6. For each experiment the concentration and mass flowrates of each candidate VOC in the influent, effluent, and off-gas were calculated. The VOC concentrations of influent and effluent samples taken at the beginning and end of the off-gas sampling interval were averaged to obtain a single influent and effluent concentration for each candidate VOC. If duplicate off-gas sampling cartridges were analyzed, these concentration measurements were also averaged to obtain a single off-gas concentration for each VOC. The VOC concentration data from the dosed tap water experiments are presented in Appendix A.1.

3.2.1 Mass Balance Closure

For each VOC the mass balance closure was defined as the sum of the measured off-gas VOC mass flow and the measured effluent VOC mass flow all divided by the total measured influent VOC mass flow. Table 3.7 contains a sample calculation of the mass balance closure.

The mass balance closure of each candidate VOC for each dosed tap water experiment is shown in Table 3.8. The average mass balance closures ranged from 67% to 123%. The overall average mass balance closure was 84% suggesting acceptable sampling and analytical accuracy. The highest standard deviations of 50 and 35 occurred for tetrachloroethylene and 1,1,1-trichloroethane which had the lowest target dose concentrations of 5 and 10 µg/L suggesting that data variability increased as the effluent concentration approached the analytical detection limit.

3.2.2 Gas-Liquid Phase Partitioning and Diffuser Type

For each dosed tap water experiment, the average ratio of off-gas concentration to effluent concentration (C_{og}/C_{ef}) of each candidate VOC was calculated. The effluent concentration represented the aeration basin contents concentration because the aeration basin contents were completely mixed. Thus, C_{og}/C_{ef} represents the observed partitioning coefficient between the VOC concentration in the gas phase and the VOC concentration in the liquid phase.

Table 3.9 presents the average ratio of off-gas concentration to effluent concentration (C_{og}/C_{ef}) of each candidate VOC for dosed tap water experiments employing the coarse or fine bubble diffusers. The experiments carried out at an aeration basin temperature near 9 °C have been separated from the two experiments carried out at an aeration basin temperature near 20 °C. For all

Table 3.6- Pilot Plant Dosed Tap Water Experiments

Experiment Number	Diffuser Bubble Type	Airflow Rate $(m^3/m^3 min)$	Oxygen $K_L aV/Q_g$	Aeration Basin Temperature (°C)
II-A.1	Coarse	0.09	1.7	8.5
II-A.2	Fine	0.05	3.5	8.0
II-A.3	Fine	0.02	3.5	9.0
II-A.4	Coarse	0.03	1.7	9.5
II-A.5	Fine	0.05	3.5	9.5
II-A.6	Coarse	0.03	1.7	10.2
II-A.7	Coarse	0.09	2.2	19.0
II-A.8	Fine	0.02	4.5	18.5

Table 3.7-Sample Mass Balance Closure Calculation;
Pilot Plant Dosed Tap Water Experiment

Effluent Flowrate=13.5 L/min
Air Flowrate=300 L/min

	Influent	Effluent	Off-gas
	Concentration		
	(ug/L)	(ug/L)	(ng/L)
Dichloromethane:	70	25	1800
	Flowrate		
	(ug/min)	(ug/min)	(ug/min)
	945	338	540

Mass Balance Closure (%)	Influent Stripped (%)
93	57

Table 3.8-Mass Balance Closure of The Candidate VOCs; Pilot Plant Dosed Tap Water Experiments

	Experiment Number									
	1	2	3	4	5	6	7	8	Avg	Std Dev
Toluene	72	61	79	58	71	70	71	56	67	7
Trichloroethylene	81	51	21	53	86	105	82	68	68	21
1,3,5-Trimethylbenzene	88	43	79	62	63	66	85	71	69	13
p-Xylene	94	54	83	58	79	77	92	60	74	14
Chloroform	74	81	30	100	66	143	50	66	76	31
4-Ethyl Toluene	111	48	86	62	68	73	99	63	76	19
1,1,1-Trichloroethane	162	96	62	68	110	86	36	64	85	35
1,4-Dichlorobenzene	109	73	77	100	87	89	144	96	96	20
Dichloromethane	78	124	114	120	135	42	127	90	103	29
Tetrachloroethylene	218	72	80	85	144	185	101	99	123	50

Table 3.9-The Ratio of Off-gas To Effluent Concentration (C_{og}/C_{ef}) and Diffuser Type (Dosed Tap Water Experiments)

Diffuser Type	Coarse Bubble	Fine Bubble
Liquid Temperature Approximately 9°C		
Oxygen K_LaV/Q_g	1.7	3.5
Number of Experiments	3	3
	C_{og}/C_{ef} (ng/L/ug/L)	
Dichloromethane	38	47
Chloroform	34	73
1,1,1-Trichloroethane	156	302
Trichloroethylene	72	194
Toluene	53	48
Tetrachloroethylene	165	177
p-Xylene	73	65
4-Ethyl Toluene	87	66
1,3,5-Trimethylbenzene	63	48
1,4-Dichlorobenzene	54	39
Liquid Temperature Approximately 20°C		
Number of Experiments	1	1
Oxygen K_LaV/Q_g	2.2	4.5
	C_{og}/C_{ef} (ng/L/ug/L)	
Dichloromethane	57	68
Chloroform	90	83
1,1,1-Trichloroethane	184	366
Trichloroethylene	277	198
Toluene	382	152
Tetrachloroethylene	554	673
p-Xylene	*---	196
4-Ethyl Toluene	---	263
1,3,5-Trimethylbenzene	---	216
1,4-Dichlorobenzene	115	106

*- data discarded because of error in liquid sample analysis

VOCs, the gas-liquid phase partition constants (C_{og}/C_{ef}) were higher at 20 °C suggesting that increased liquid temperature increased the gas phase partitioning of the VOCs. At 20 °C, the four compounds displaying the greatest gas phase partitioning were tetrachloroethylene, 1,1,1-trichloroethane, toluene and trichloroethylene which also had the highest reported Henry's Law coefficients. At a liquid temperature near 9°C, the compounds displaying the greatest gas phase partitioning were again tetrachloroethylene, 1,1,1-trichloroethane and trichloroethylene. Toluene displayed much lower gas phase partitioning at the reduced liquid temperature. The reason for the observed sharp decrease in toluene's gas phase partitioning with liquid temperature was not apparent.

For experiments carried out at a liquid temperature near 9 °C, the effect of diffuser type on the gas-liquid phase partitioning constants (C_{og}/C_{ef}) was examined using T-tests presented in Table 3.10. For all 10 VOCs, there was little evidence (null hypothesis-no effect; $0.23 < P < 0.89$) that diffuser type affected the gas-liquid phase partitioning of the VOCs. This implies that the greater gas-liquid phase mass transfer efficiency of the fine bubble diffusers (indicated by the greater oxygen K_LaV/Q_g) did not increase the gas phase partitioning of the VOCs. This suggests that equilibrium existed between the VOC gas and liquid phases with both diffuser types. At a liquid temperature of 20°C there were insufficient data to determine a variance for use in the T-tests. However, four VOCs had a higher C_{og}/C_{ef} when the coarse bubble diffuser system was employed and three VOCs had a higher C_{og}/C_{ef} when the fine bubble diffuser system was employed. Thus, again there was no evidence that the diffuser type affected the gas-liquid phase partitioning of the VOCs.

Fractional saturation of a VOC was defined as the observed ratio of off-gas concentration to effluent concentration (C_{og}/C_{ef})

Table 3.10-Testing the Effect of Diffuser Type On VOC Gas-Liquid Phase Partitioning Coefficients (Dosed Tap Water Experiments; 9°C Liquid Temperature)

Diffuser Type	Coarse Bubble	Fine Bubble
Experiment Numbers	II-A.1 II-A.4 II-A.6	II-A.2 II-A.3 II-A.5
Oxygen K_laV/Q_g	1.7	3.5

Null Hypothesis: No effect of diffuser type on C_{eg}/C_{ef}

Reject Null Hypothesis at 95% Confidence Level if $P < 0.05$

	C_{eg}/C_{ef} (ng/L/µg/L)				pooled variance	test statistic	Null Hypothesis Probability value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	38	15	47	17	266	-0.6	0.58
Chloroform	34	7	73	78	3105	-0.9	0.41
1,1,1-Trichloroethane	156	70	302	288	43941	-0.9	0.41
Trichloroethylene	72	9	194	231	26800	-0.9	0.42
Toluene	53	8	48	15	147	0.5	0.65
Tetrachloroethylene	165	55	177	102	6792	-0.1	0.89
p-Xylene	73	12	65	22	327	0.5	0.61
4-Ethyl Toluene	87	22	66	19	414	1.3	0.26
1,3,5-Trimethylbenzene	63	11	48	15	171	1.4	0.23
1,4-Dichlorobenzene	54	12	39	15	196	1.3	0.27

divided by the reported Henry's Law constant (H) for that VOC. For the comparison of C_{og}/C_{ef} to H to be valid, the experiment must have been carried out at a liquid temperature near 20 °C, the temperature at which Henry's Law constants reported in the literature are measured. A fractional saturation exceeding 1.0 implies that the observed off-gas concentration exceeded the Henry's Law prediction of off-gas concentration. A fractional saturation below 1.0 implies that the observed off-gas concentration was lower than the Henry's Law prediction of off-gas concentration. Table 3.11 presents the observed fractional saturations for the two dosed tap water experiments carried out at an aeration basin temperature near 20 °C. Henry's Law coefficients were not available for 1,3,5-trimethylbenzene and p-xylene, and these compounds are not presented in Table 3.11. The average observed fractional saturations exceeded 1.0 for three compounds (1,1,1-trichloroethane, toluene and 1,4-dichlorobenzene) and were below 1.0 for the remaining five compounds. Thus, although it appeared that equilibrium existed between the VOC gas and liquid phases, the observed gas-liquid phase partition constants differed from Henry's Law values obtained from the literature.

3.2.3 Airflow Rate and Percentage Stripped

The fraction of each candidate VOC stripped from the pilot plant aeration basin was defined as the ratio of the measured VOC off-gas mass flow divided by the measured VOC influent mass flow. A sample calculation of percentage stripped is contained in Table 3.7. Table 3.12 lists the dosed tap water experiments from left to right in order of increasing airflow rate, and, for a given airflow rate, lists the average percentage stripped of each VOC. No distinction was made between diffuser types in Table 3.12 because there was no evidence of an effect of diffuser type on the partitioning of the VOCs between the gas and liquid phases. The

Table 3.11- Observed VOC Fractional Saturation $((C_{eg}/C_{e\ell})/H)$; Dosed Tap Water Experiments

		Experiment Number		
		7	8	Avg
Diffuser Type		Coarse	Fine	
	H	$((C_{eg}/C_{e\ell})/H)$		
Dichloromethane	130	0.44	0.52	0.48
Chloroform	140	0.64	0.59	0.62
1,1,1-Trichloroethane	200	0.92	1.83	1.37
Trichloroethylene	380	0.73	0.52	0.63
Toluene	250	1.53	0.61	1.07
Tetrachloroethylene	1190	0.47	0.57	0.52
p-Xylene	220	*---	0.89	0.89
1,4-Dichlorobenzene	110	1.05	0.96	1.01

*- data discarded because of error in effluent sample analysis

Table 3.12-Percentage of The Influent Mass Flow of VOCs Stripped and Airflow Rate; Dosed Tap Water Experiments

Liquid Temperature Approximately 9 °C

Experiment Numbers	II-A.3	II-A.4 II-A.6	II-A.2 II-A.5	II-A.1	
Airflow $(m^3/m^3\text{min})$	0.019	0.033	0.052	0.093	Avg
	Percentage Stripped				
Dichloromethane	19	34	61	50	43
Chloroform	14	36	25	38	29
1,1,1-Trichloroethane	48	53	74	119	70
Trichloroethylene	15	37	36	58	37
Toluene	17	24	30	49	29
Tetrachloroethylene	43	95	77	172	93
p-xylene	21	30	36	70	37
4 Ethyl Toluene	24	32	31	88	40
1,3,5-Trimethylbenzene	17	26	25	64	31
1,4-Dichlorobenzene	15	34	32	76	37
Average	23	40	42	78	

Liquid Temperature Approximately 20°C

Experiment Numbers	II-A.8	II-A.7	
Airflow $(m^3/m^3\text{min})$	0.022	0.091	Avg
	Percentage Stripped		
Dichloromethane	29	85	57
Chloroform	25	38	32
1,1,1-Trichloroethane	46	31	39
Trichloroethylene	40	75	58
Toluene	29	66	48
Tetrachloroethylene	82	96	89
p-Xylene	35	88	62
4-Ethyl Toluene	41	96	69
1,3,5-Trimethylbenzene	43	84	64
1,4-Dichlorobenzene	41	116	78
Average	41	77	

experiments carried out at an aeration basin temperature near 9 °C have been separated from the two experiments carried out at an aeration basin temperature near 20 °C.

At both 9 °C and 20 °C, chloroform was stripped to the least extent while tetrachloroethylene was stripped to the greatest extent. Scanning Table 3.12 from left to right reveals that the percentage of each VOC stripped from the aeration basin increased with increased airflow rate, but the relative increase in percentage stripped was less than the relative increase in airflow rate. That is, for example, a four fold increase in airflow rate caused a substantial increase in the amount of stripping but less than four fold. At nearly equivalent airflow rates, comparing the experiments carried out at a liquid temperature near 20 °C to those carried out at a liquid temperature near 9 °C (experiment A-8 to experiments A-3,A-4,A-6 and run A-7 to run A-1) shows that for most VOCs the percentage stripped increased as the aeration basin temperature increased. The average percentage of compounds stripped in Experiments A.1 and A.7 were similar because of the unusually high value recorded for tetrachloroethylene in experiment A-1 and the unusually low value recorded for 1,1,1-trichloroethane in experiment A-7.

3.3 Burlington Skyway Wastewater Results

3.3.1 Pilot Plant Dosed and Non-Dosed Wastewater Experiments; 5 day SRT and 10 day SRT

Eight pilot plant dosed wastewater experiments and two pilot plant non-dosed wastewater experiments were performed using wastewater from the Burlington Skyway WPCP when the plant was operated at a 5 day SRT. Five pilot plant dosed wastewater experiments were performed when the plant was operated at a 10 day SRT. The experimental conditions are summarized in Tables 3.13a and 3.13b. All ten candidate VOCs were detected in the non-dosed

Table 3.13a-Pilot Plant Dosed and Non-Dosed Wastewater Experiments
(Burlington Skyway Wastewater, 5 day SRT)

Experiment Number	Diffuser Bubble Type	Airflow Rate (m^3/m^2min)	Oxygen $\alpha K_L aV/Q_s$	Mixed Liquor Temperature (°C)
Dosed Wastewater				
II-B.1.1	Coarse	0.06	1.1	19.0
II-B.1.2	Coarse	0.12	1.1	18.0
II-B.1.3	Coarse	0.04	1.1	18.0
II-B.1.4	Coarse	0.13	1.1	18.0
II-B.1.5	Fine	0.10	1.2	20.0
II-B.1.6	Fine	0.03	1.2	20.0
II-B.1.7	Fine	0.10	1.4	25.5
II-B.1.8	Coarse	0.04	1.3	25.0
Non-Dosed Wastewater				
II-B.1.9	Coarse	0.04	1.1	19.0
II-B.1.10	Coarse	0.12	1.1	20.5

Table 3.13b-Pilot Plant Dosed Wastewater Experiments
(Burlington Skyway Wastewater, 10 day SRT)

Experiment Number	Diffuser Bubble Type	Airflow Rate (m^3/m^2min)	Oxygen $\alpha K_L aV/Q_s$	Mixed Liquor Temperature (°C)
II-B.2.1	Fine	0.09	1.0	17.5
II-B.2.2	Fine	0.09	1.0	16.0
II-B.2.3	Coarse	0.10	0.9	15.5
II-B.2.4	Coarse	0.03	0.9	16.5
II-B.2.5	Fine	0.03	1.0	17.0

influent. Influent concentrations were generally below 10 µg/L, except for dichloromethane which occasionally exceeded 100 µg/L.

For each experiment the concentration and mass flowrates of each candidate VOC in the influent, effluent, waste activated sludge and off-gas were calculated. The VOC concentrations of influent and effluent samples taken at the beginning and end of the off-gas sampling interval were averaged to obtain a single influent and effluent concentration for each candidate VOC. If duplicate off-gas sampling cartridges were analyzed, these concentration measurements were also averaged to obtain a single off-gas concentration for each VOC. The VOC concentration data from all pilot plant experiments employing Burlington Skyway WPCP wastewater are contained in Appendices A.2 to A.4.

3.3.1.1 Mass Balance Closure

For each VOC the mass balance closure was defined as the sum of the measured off-gas VOC mass flow plus the measured effluent VOC mass flow and the measured waste activated sludge VOC mass flow all divided by the total measured influent VOC mass flow. Table 3.14 presents a sample calculation of the mass balance closure. VOC concentrations in the waste activated sludge and effluent are presented in Appendix A, and values from a typical dosed wastewater experiment are presented in Table 3.15. For all the candidate VOCs, the measured concentrations in the waste activated sludge were more variable than the effluent concentrations but not significantly higher. Since the volume of sludge wasted daily to maintain a 5 or 10 day SRT is much less than the effluent flow, sorption on the waste activated sludge was not regarded as a major VOC removal mechanism.

Table 3.14-Sample Mass Balance Closure Calculation; Pilot Plant Wastewater Experiment

Effluent Flowrate=13.5 L/min
Air Flowrate=400 L/min
Estimated waste activated sludge flowrate=0.14 L/min.

	Influent	Effluent	Off-gas	WAS
	Concentration			
	(µg/L)	(µg/L)	(ng/L)	(µg/L)
Dichloromethane	63	6	553	7
	Flowrate			
	(µg/min)	(µg/min)	(µg/min)	(µg/min)
Dichloromethane	851	81	221	1

	Mass Balance Closure (%)	Influent Stripped (%)
Dichloromethane	36	26

Table 3.15- Concentration of VOCs in the Effluent and Waste Activated Sludge For a Typical Pilot Plant Experiment (II-B.1.8)

	Effluent Conc. (µg/L)	WAS Conc. (µg/L)
Dichloromethane	4.8	5.1
Chloroform	8.5	5.4
1,1,1-Trichloroethane	2.8	2.4
Trichloroethylene	4.5	3.3
Toluene	1.8	2.5
Tetrachloroethylene	4.2	3.1
p-Xylene	< .2	< .2
4-Ethyl Toluene	< .2	< .2
1,3,5-Trimethylbenzene	< .2	< .2
1,4-Dichlorobenzene	3.6	2.7

5 day SRT

The mass balance closure of each candidate VOC for each dosed and non-dosed wastewater experiment carried out at a 5 day SRT is shown in Table 3.16. The reason for excluding toluene from Table 3.16 will be discussed later in this section. For 5 of the 9 candidate VOCs, the average mass balance closure of the dosed wastewater experiments exceeded the average mass balance closure of the non-dosed wastewater experiments. For the remaining 4 candidate VOCs the average mass balance closure of the non-dosed wastewater experiments exceeded the average mass balance closure of the dosed wastewater experiments. This suggests that the elevated influent VOC concentrations caused by dosing were not influencing the mass balance closure results. The effect of the elevated influent concentrations caused by dosing on the mass balance closures of the VOCs was examined using T-tests presented in Table 3.17. For seven VOCs there was little evidence (null hypothesis: no effect of dosing; $0.13 < P < 0.89$) that dosing affected the average mass balance closures. For 4-ethyl toluene and p-xylene there was indication ($0.03 < P < 0.09$) that mass balance closures were higher during non-dosed experiments. Thus, it was concluded that the elevated influent VOC concentration caused by dosing may have marginally affected the mass balance closures of some VOCs but did not distort results to any degree.

In Table 3.16, the average mass balance closures for 4-ethyl toluene, 1,3,5-trimethylbenzene and p-xylene were below 11%, and well below those values observed during dosed tap water experiments (Table 3.8), suggesting substantial biological removal of these compounds. The average mass balance closure for the remaining 6 VOCs ranged from 55% to 102%. These mass balance closures were moderately lower than those values observed during dosed tap water experiments (Table 3.9) suggesting limited biological removal, if any, of these VOCs.

Table 3.16-Mass Balance Closures of The Candidate VOCs (Pilot Plant Dosed and Non-Dosed Wastewater Experiments; Burlington Skyway Wastewater, 5 day SRT

Experiment Number	1	2	3	4	5	6	7	8	Avg	9	10	Avg	Overall Avg.
	Dosed									Non-Dosed			
Tetrachloroethylene	29	71	104	200	130	172	85	50	105	77	103	90	102
1,4-Dichlorobenzene	127	51	126	*--	73	81	90	117	95	75	91	83	92
Trichloroethylene	15	31	42	139	130	101	61	50	71	48	85	66	70
Chloroform	51	38	141	90	81	67	46	59	72	58	39	49	67
1,1,1-Trichloroethane	4	37	25	45	85	121	41	52	51	63	82	73	55
Dichloromethane	48	79	76	107	27	51	52	*--	63	22	37	29	55
p-Xylene	3	4	2	27	3	4	13	7	8	10	38	24	11
4-Ethyl Toluene	2	2	1	4	1	2	1	2	2	3	5	4	3
1,3,5-Trimethylbenzene	2	3	1	9	3	3	7	5	4	4	10	7	4

*- data discarded because of error in liquid sample analysis

Table 3.17-Testing the Effect of Dosing On The Average Mass Balance Closure For Each Candidate VOC

Null Hypothesis: No Effect of Dosing On Average Mass Balance Closure of The VOC

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Dosed Wastewater		Non-Dosed Wastewater				
Experiment Numbers	II-B.1.1 to II-B.1.8		II-B.1.9 to II-B.1.10				
	Mass Balance Closure				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	105	59	90	18	3104	0.34	0.74
1,4-Dichlorobenzene	95	29	83	11	747	0.55	0.60
Trichloroethylene	71	46	67	26	1975	0.13	0.89
Chloroform	72	33	49	13	977	0.93	0.76
1,1,1-Trichloroethane	51	36	73	13	1181	-0.78	0.46
Dichloromethane	63	26	30	11	609	1.69	0.13
p-Xylene	8	8	24	20	112	-1.92	0.09
4-Ethyl Toluene	2	1	4	1	1	-2.55	0.03
1,3,5-Trimethylbenzene	4	3	7	4	8	-1.23	0.25

Mass balance closures during wastewater and dosed tap water experiments were compared using T-tests presented in Table 3.18. For p-xylene, 4-ethyl toluene and 1,3,5-trimethylbenzene there was conclusive evidence (null hypothesis: equal mass balance closures; $P < 0.01$) that mass balance closures were lower during wastewater experiments confirming that substantial biological removal of these VOCs occurred. For dichloromethane and 1,1,1-trichloroethane there was indication ($0.02 < P < 0.09$) that mass balance closures were lower during wastewater experiments suggesting limited biological removal of these VOCs. For tetrachloroethylene, 1,4-dichlorobenzene, trichloroethylene and chloroform there was little indication ($0.53 < P < 0.90$) that mass balance closures were lower during wastewater experiments suggesting minimal biological removal of these VOCs.

For most of this experimental phase, high concentrations of toluene were recorded in the blank off-gas cartridges. The source of the high blank concentrations was discovered to be a leak in the laboratory thermal desorber which was contaminating the Tenax. For the first experiment, which was carried out before the high toluene off-gas blank concentrations were observed, the mass balance closure for toluene was 5% suggesting extensive biological removal. For the remaining experiments in this phase, the toluene effluent concentrations were much lower (frequently below analytical detection limit) than those observed in the dosed tap water experiments again suggesting significant biological removal of toluene.

Eleven volatiles, other than the candidate ten, included on the MOE Effluent Monitoring Priority Pollutant list (Ontario Ministry of Environment, 1988a) were observed in the pilot plant influent during this experimental phase. Average mass balance closures for these VOCs, shown in Table 3.19, were consistently less than 10% suggesting substantial biological removal of these

Table 3.18-Comparing VOC Mass Balance Closures During Dosed Wastewater Experiments (Burlington Skyway Wastewater, 5 day SRT) To Mass Balance Closures During Dosed Tap Water Experiments

Null Hypothesis: Mass Balance Closures Are Equal For Tap Water and Wastewater Experiments

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Wastewater		Dosed Tap Water				
Experiment Numbers	II-B.1.1 to II-B.1.10		II-A.1 to II-A.8				
	Mass Balance Closure				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	102	53	123	54	3197	-0.63	0.53
1,4-Dichlorobenzene	92	26	97	22	661	-0.13	0.90
Trichloroethylene	70	42	68	26	1421	0.15	0.89
Chloroform	67	31	76	34	1122	-0.27	0.78
1,1,1-Trichloroethane	55	36	86	38	1400	-1.83	0.09
Dichloromethane	55	27	103	31	854	-2.70	0.02
p-Xylene	8	12	74	15	157	-10.66	0.00
4-Ethyl Toluene	3	1	76	21	220	-10.02	0.00
1,3,5-Trimethylbenzene	4	3	70	15	110	-12.49	0.00

Table 3.19-Mass Balance Closures For the Non-Candidate VOCs
During Pilot Plant Wastewater Experiments
(Burlington Skyway Wastewater, 5 day SRT)

	Mass Balance Closure (%)
Ethyl Benzene	< 10
m-Xylene	< 10
o-Xylene	< 10
Propyl Benzene	< 10
Isopropyl Benzene	< 10
2-Ethyl Toluene	< 10
3-Ethyl Toluene	< 10
1,2,3-Trimethylbenzene	< 10
1,2,4-Trimethylbenzene	< 10
1.3-Diethylbenzene	< 10
1,4-Diethylbenzene	< 10

VOCs. Thus, including candidate and non-candidate VOCs, the 15 VOCs displaying extensive biological removal were all non-halogenated alkylaromatic organics, and the 6 VOCs displaying incomplete biological removal were chlorinated aromatics and aliphatics.

10 day SRT

The mass balance closure of each candidate VOC for each dosed wastewater experiment carried out at a 10 day SRT is shown in Table 3.20. Average mass balance closures at a 10 day SRT were compared to mass balance closures at a 5 day SRT using T-tests presented in Table 3.21. For 1,4-dichlorobenzene, chloroform, p-xylene and 1,3,5-trimethylbenzene there was only marginal indication (null hypothesis: no effect of SRT; $0.11 < P < 0.14$) that mass balance closures were lower at a 10 day SRT. For the remaining 5 VOCs there was little indication ($P > 0.84$) that mass balance closures were lower at the increased SRT. Thus, in general, there was no evidence that mass balance closures were lower at the increased SRT. However, the experiments were not explicitly designed to examine the effect of SRT and the confounding variables (especially the difference in airflow rate between experiments) may have concealed an effect. A more sophisticated statistical analysis (involving a model accounting for the effect of airflow rate and non-linear parameter fitting) is required to rigorously evaluate the SRT effect.

3.3.1.2 Gas-Liquid Phase Partitioning and Diffuser Type

The gas-liquid phase partitioning coefficient ($C_{eg}/C_{e\ell}$) of the VOCs was defined as in Section 3.2.2. For each dosed and non-dosed wastewater experiment (5 and 10 day SRT), $C_{eg}/C_{e\ell}$ was calculated for experiments employing the coarse and the fine bubble diffuser systems, and the results are presented in Table 3.22. Experiments

Table 3.20-Mass Balance Closure For The Candidate VOCs At a 10 day SRT (Pilot Plant Dosed Wastewater Experiments; Burlington Skyway Wastewater)

Experiment Number	1	2	3	4	5	Avg	Std Dev
Tetrachloroethylene	74	98	140	114	57	97	32
1,4-Dichlorobenzene	*--	86	101	43	37	67	27
Trichloroethylene	74	61	100	75	23	67	28
Chloroform	43	48	63	36	42	46	9
1,1,1-Trichloroethane	66	70	61	52	30	56	16
Dichloromethane	*--	74	81	39	36	57	20
Toluene	16	11	12	5	3	9	5
p-Xylene	6	3	4	2	1	3	2
4-Ethyl Toluene	4	2	3	1	1	2	1
1,3,5-Trimethylbenzene	4	2	3	1	2	2	1

*- data discarded because of error in liquid sample analysis

Table 3.21-Testing The Effect of Solids Retention Time On VOC Mass Balance Closures; (Pilot Plant Experiments Using Burlington Skyway Wastewater, 5 and 10 day SRT)

Null Hypothesis: No Effect of SRT On Average Mass Balance Closures

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

	5 day SRT		10 day SRT				
Experiment Numbers	II-B.1.1 to II-B.1.10		II-B.2.1 to II-B.2.5				
	Mass Balance Closure				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	102	53	97	32	2267	0.21	0.84
1,4-Dichlorobenzene	92	26	67	27	704	1.73	0.11
Trichloroethylene	70	42	67	28	1462	0.17	0.86
Chloroform	67	31	46	9	649	1.57	0.14
1,1,1-Trichloroethane	55	36	56	16	861	-0.01	0.98
Dichloromethane	55	27	57	20	635	-0.14	0.89
p-Xylene	11	12	3	2	95	1.57	0.14
4-Ethyl Toluene	2	1	2	1	2	0.13	0.89
1,3,5-Trimethylbenzene	5	3	2	1	7	1.62	0.13

Table 3.22-The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}) (Pilot Plant Experiments Using Burlington Skyway Wastewater, 5 and 10 day SRT)

Diffuser Type	Coarse Bubble	Fine Bubble
Mixed Liquor T= 16°C	C_{og}/C_{ef} (ng/L/ug/L)	
Number of Experiments	2	3
Dichloromethane	120	44
Chloroform	66	88
1,1,1-Trichloroethane	284	187
Trichloroethylene	252	344
Tetrachloroethylene	575	534
1,4-Dichlorobenzene	101	138
Mixed Liquor T= 20°C	C_{og}/C_{ef} (ng/L/ug/L)	
Number of Experiments	6	2
Dichloromethane	109	40
Chloroform	75	66
1,1,1-Trichloroethane	191	40
Trichloroethylene	268	212
Tetrachloroethylene	443	493
1,4-Dichlorobenzene	149	111
Mixed Liquor T= 25°C	C_{og}/C_{ef} (ng/L/ug/L)	
Number of Experiments	1	1
Dichloromethane	356	73
Chloroform	72	111
1,1,1-Trichloroethane	94	177
Trichloroethylene	154	277
Tetrachloroethylene	227	1176
1,4-Dichlorobenzene	144	191

have been separated according to mixed liquor temperature. For toluene, p-xylene, 4-ethyl toluene, and 1,3,5-trimethylbenzene the effluent concentrations were generally below the analytical detection limits because of the substantial biological removal, and C_{eq}/C_{ef} is not reported for these VOCs. As observed during dosed tap water experiments, the VOCs displaying the greatest gas-phase partitioning were 1,1,1-trichloroethane, trichloroethylene and tetrachloroethylene which also had the highest reported Henry's Law coefficients.

The effect of diffuser type on gas-liquid phase partitioning of the VOCs was examined using T-tests presented in Tables 3.23a and 3.23b. There were insufficient data to examine the effect of diffuser type at 25 °C. For all VOCs, at 16 °C and 20 °C, there was little indication (null hypothesis: no effect of diffuser type; $P > 0.12$) of an effect of diffuser type on the gas-liquid phase partitioning of the VOCs although the temperature difference was not large and the data highly variable. The similar gas-liquid phase partitioning of the VOCs with the different diffuser types is not unexpected because the gas-liquid phase mass transfer efficiencies of the coarse and fine bubble diffusers were similar (indicated by the similar oxygen $\alpha K_L aV/Q_g$) when Burlington Skyway WPCP wastewater was the pilot plant feed source.

The effect of mixed liquor temperature (17 °C vs 25 °C) on the gas-liquid phase partitioning of the VOCs was examined using T-tests presented in Table 3.24. For all the VOCs, there was little indication (null hypothesis: no effect of temperature; $P > 0.13$) of an effect of mixed liquor temperature on gas-liquid phase partitioning of the VOCs. This contradicts the observation made during dosed tap water experiments. Perhaps, the effect over the temperature range of 17 °C to 25 °C is less than the effect over the temperature range of 9 °C to 20 °C and was obscured by data

Table 3.23a- Testing the Effect of Diffuser Type On The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}) (Pilot Plant Experiments Using Burlington Skyway Wastewater, 5 day SRT)

Null Hypothesis: No effect of diffuser type on C_{og}/C_{ef}

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

Mixed Liquor Temperature = 20°C

	Coarse Bubble		Fine Bubble				
Number of Experiments	6		2				
Oxygen $\alpha K_L aV/Q_g$	1.1		1.2				
	C_{og}/C_{ef} (ng/L/µg/L)				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	109	77	41	31	5170	1.16	0.28
Chloroform	75	43	66	62	2196	0.23	0.82
1,1,1-Trichloroethane	191	113	41	31	10835	1.77	0.12
Trichloroethylene	268	63	213	192	9502	0.70	0.51
Tetrachloroethylene	443	256	393	393	80541	0.22	0.83
1,4-Dichlorobenzene	149	115	111	24	11252	0.44	0.67

Table 3.23b- Testing the Effect of Diffuser Type On The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}) (Pilot Plant Experiments Using Burlington Skyway Wastewater, 10 day SRT)

Null Hypothesis: No effect of diffuser type on C_{og}/C_{ef}

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

Mixed Liquor Temperature = 16°C

	Coarse Bubble	Fine Bubble
Number of Experiments	2	3
Oxygen $\alpha K_L aV/Q_g$	0.9	1.0

	C_{og}/C_{ef} (ng/L/µg/L)				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Chloroform	88	40	67	3	914	0.78	0.49
1,1,1-Trichloroethane	284	161	187	186	29135	0.62	0.58
Trichloroethylene	253	83	344	21	4694	-1.46	0.24
Tetrachloroethylene	575	359	534	215	101812	0.14	0.89
1,4-Dichlorobenzene	101	39	139	1	1033	-1.25	0.29

Table 3.24- Testing The Effect of Mixed Liquor Temperature On The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}); Pilot Plant Experiments Using Burlington Skyway Wastewater

Null Hypothesis: No effect of mixed liquor temperature on C_{og}/C_{ef}

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Temp = 17 °C		Temp = 25 °C				
No. of experiments	5		2				
	C_{og}/C_{ef} (ng/L/ug/L)				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	89	39	214	199	14282	-1.14	0.33
Chloroform	80	29	92	27	812	-0.51	0.64
1,1,1-Trichloroethane	245	157	135	58	20430	0.92	0.40
Trichloroethylene	289	72	215	87	6314	1.11	0.32
Tetrachloroethylene	559	277	701	671	151448	-0.43	0.68
1,4-Dichlorobenzene	117	34	168	32	1156	-1.82	0.13

variability.

Fractional saturation of a VOC was defined as in Section 3.2.2. Table 3.25 presents the average observed fractional saturations for the wastewater experiments carried out at an aeration basin temperature near 20 °C. There was considerable variability in the data, and the average fractional saturations ranged from 0.4 to 0.9. The VOCs 1,4-dichlorobenzene and 1,1,1-trichloroethane exhibited fractional saturation values closest to 1.0 while chloroform and tetrachloroethylene deviated furthest from the Henry's Law prediction of off-gas concentration. Fractional saturations observed during wastewater experiments were compared to fractional saturations observed during dosed tap water experiments using T-tests presented in Table 3.26. For all the VOCs examined there was little indication (null hypothesis: equal fractional saturations; $P > 0.50$) that fractional saturations were higher during dosed tap water experimentation. Thus there was little evidence that the greater gas-liquid phase mass transfer efficiency of the tap water experiments, indicated by the greater oxygen K_LaV/Q_g, increased the gas phase partitioning of the VOCs. This suggests that equilibrium existed between the VOC gas and liquid phases over this range of mass transfer conditions.

3.3.1.3 Airflow Rate and Percentage Stripped

The fraction of each candidate VOC stripped from the pilot plant aeration basin was defined as in Section 3.2.3. A sample calculation of percentage stripped is contained in Table 3.14. For a 5 day SRT, Table 3.27a lists the Burlington Skyway wastewater experiments from left to right in order of increasing airflow rate, and, for a given airflow rate, lists the average percentage stripped of each VOC. Experiments carried out at a mixed liquor temperature near 20 °C have been separated from those carried out near 25 °C. The average percentage of each VOC stripped from the

Table 3.25-Observed VOC Fractional Saturation $((C_{og}/C_{ef})/H)$; (Pilot Plant Dosed Experiments Using Burlington Skyway Wastewater)

		Dosed	Non-Dosed	Average
No. of Experiments		6	2	
	H	$((C_{og}/C_{ef})/H)$		
Dichloromethane	130	0.4	1.5	0.7
Chloroform	140	0.3	0.8	0.4
1,1,1-Trichloroethane	200	0.8	1.4	0.9
Trichloroethylene	380	0.7	0.7	0.7
Tetrachloroethylene	1190	0.3	0.6	0.4
1,4-Dichlorobenzene	110	0.8	1.2	0.9

Table 3.26- Comparing VOC Fractional Saturation ($(C_{og}/C_{el})/H$) Observed During Pilot Plant Experiments Using Burlington Skyway Wastewater To That Observed During Dosed Tap Water Experiments

Null Hypothesis: No difference in fractional saturation

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

	Wastewater		Tap Water				
Range of Oxygen $\alpha K_L aV/Q_g$	1.1-1.4		2.2-4.5				
Number of Experiments	8		2				
	Fractional Saturation				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	0.71	0.56	0.48	0.06	0.28	0.53	0.61
Chloroform	0.52	0.31	0.62	0.04	0.08	-0.41	0.69
1,1,1-Trichloroethane	1.06	0.52	1.37	0.64	0.29	-0.71	0.50
Trichloroethylene	0.67	0.24	0.62	0.15	0.05	0.23	0.82
Tetrachloroethylene	0.36	0.22	0.52	0.07	0.04	-0.98	0.36
1,4-Dichlorobenzene	0.94	0.28	1.00	0.06	0.07	-0.20	0.85

Table 3.27a- Percentage of The Influent Mass Flow of The Candidate VOCs Stripped and Airflow Rate (Pilot Plant Experiments Using Burlington Skyway Wastewater, 5 day SRT)

Mixed Liquor Temperature= 20°C

Number of Experiments	4	4	
Airflow (m^3/m^3min)	0.03-0.06	0.10-0.13	
	Percentage Stripped		
			Avg
Tetrachloroethylene	53	111	82
1,4-Dichlorobenzene	52	56	54
Trichloroethylene	21	59	40
Chloroform	37	41	39
1,1,1-Trichloroethane	39	45	42
Dichloromethane	24	47	36
p-Xylene	5	17	11
4-Ethyl Toluene	2	4	3
1,3,5-Trimethylbenzene	2	4	3
Average	24	38	

Mixed Liquor Temperature= 25°C

Number of Experiments	1	1	
Airflow (m^3/m^3min)	0.04	0.10	
	Percentage Stripped		
			Avg
Tetrachloroethylene	34	71	53
1,4-Dichlorobenzene	71	68	70
Trichloroethylene	31	48	40
Chloroform	27	33	30
1,1,1-Trichloroethane	27	31	29
Dichloromethane	*--	34	--
p-Xylene	6	11	9
4-Ethyl Toluene	< 1	3	2
1,3,5-Trimethylbenzene	4	6	5
Average	22	**30	

*- data discarded because of error in off-gas sample analysis

**- Dichloromethane not included in average aeration basin during 10 day SRT experiments is shown in Table 3.27b. No distinction was made between diffuser types in Tables 3.27a or 3.27b because there was no evidence of an effect of diffuser type on the partitioning of the VOCs between the gas and liquid phases.

The VOCs displaying the greatest amount of stripping were tetrachloroethylene and 1,4-dichlorobenzene. Compounds stripped the least, due to competing biological removal were 4-Ethyl toluene, 1,3,5-trimethylbenzene and p-xylene. At the low airflow rate of approximately 0.04 m^3/m^3min, less than 5% of the influent mass flow of these compounds was stripped from the aeration basin. As observed during dosed tap water experiments, scanning Tables 3.27a and 3.27b from left to right reveals that the percentage of each VOC stripped from the aeration basin generally increased with increasing airflow rate, but the relative increase in percentage stripped was generally less than the relative increase in airflow rate.

3.3.2 Burlington Skyway Full Scale Aeration Basin Sampling

Two sampling experiments were carried out at a Burlington Skyway WPCP aeration basin. Off-gas and mixed liquor samples were taken at the influent, mid-way and at the end of the full scale aeration basin (Figure 2.2). The influent to the aeration basin and the effluent from the full scale secondary settlers were also sampled. VOC concentration measurements from mixed liquor samples taken at the beginning and end of the off-gas sampling interval were averaged to obtain a single mixed liquor concentration for each candidate VOC at each sampling location. The VOC concentration data collected at the Burlington Skyway WPCP aeration basin are contained in Appendix A.5.

Table 3.28 summarizes the concentration of the candidate VOCs measured in the aeration basin influent and effluent and in the

Table 3.27b-Percentage of The Influent Mass Flow of the Candidate VOCs Stripped and Airflow Rate (Pilot Plant Experiments Using Burlington Skyway Wastewater, 10 day SRT)

Mixed Liquor Temperature= 17°C

Number of Experiments	2	3	
Airflow (m^3/m^3min)	0.03-0.04	0.10-0.12	
	Percentage Stripped		
			Avg
Tetrachloroethylene	83	97	90
1,4-Dichlorobenzene	32	79	55
Trichloroethylene	45	94	69
Chloroform	22	37	30
1,1,1-Trichloroethane	34	37	35
Dichloromethane	20	71	45
Toluene	4	10	7
p-Xylene	2	2	2
4-Ethyl Toluene	1	3	2
1,3,5-Trimethylbenzene	2	3	3
Average	24	38	

mixed liquor at sampling locations 1,2 and 3 as shown in Figure 2.2. The mixed liquor concentrations of toluene, p-xylene, 4-ethyl toluene, and 1,3,5-trimethylbenzene measured in the aeration basin were much lower than could be accounted for by stripping alone suggesting extensive biological removal of these compounds. The mixed liquor concentrations of dichloromethane, chloroform, 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene and 1,4-dichlorobenzene decreased considerably along the length of the aeration basin presumably because they were being stripped. This decrease in concentration along the length of the aeration basin is consistent with the hydraulic study that suggested that the aeration basin hydraulics could be modelled as between 1 and 2 tanks in series. The mean percentage removal of a VOC from the aeration basin was defined as:

$$\%\ \text{Removal} = [1-(C_e/C_i)]*100 \quad \text{..........................(3.1)}$$

where:

C_e = aeration basin effluent VOC concentration
C_i = aeration basin influent VOC concentration

Table 3.29 presents the mean percentage removal of each candidate VOC at the full scale aeration basin. For comparison, the mean percentage removal of the candidate VOCs in the pilot plant during dosed wastewater experiments is also presented in Table 3.29. In most cases, toluene, p-xylene, 4-ethyl toluene and 1,3,5-trimethylbenzene were nearly completely removed from the full scale aeration basin and the pilot plant because of extensive biological removal. The 6 other candidate VOCs displayed removals ranging from 42% to 98%, presumably primarily due to stripping. The percentage removal of the VOCs in the pilot plant and the full scale aeration basin were compared using T-tests presented in Table 3.30. For the 8 VOCs examined (insufficient data for p-xylene and 1,4-dichlorobenzene), there was little indication (null hypothesis: no difference in removal; $0.16 < P < 0.90$) of a difference in

Table 3.28- Variation in Candidate VOC Wastewater Concentration Along Length of Burlington Skyway Aeration Basin

Experiment 1

	Concentration (µg/L)				
	L_{in}	L_{ML1}	L_{ML2}	L_{ML3}	L_{out}
Dichloromethane	14.0	10.0	5.7	4.6	2.7
Chloroform	5.4	0.9	1.9	0.5	1.8
1,1,1-Trichloroethane	1.3	0.7	0.3	0.3	0.4
Trichloroethylene	4.6	2.9	0.9	0.9	0.3
Tetrachloroethylene	31.7	15.0	6.1	3.9	1.9
1,4-Dichlorobenzene	1.2	1.2	0.7	0.6	0.7
Toluene	12.0	0.5	0.1	0.3	0.2
p-Xylene	3.1	0.5	0.1	0.2	0.8
4-Ethyl Toluene	168.0	14.2	0.2	ND	ND
1,3,5-Trimethylbenzene	33.7	3.5	0.1	0.6	0.7

Experiment 2

	L_{in}	L_{ML1}	L_{ML2}	L_{ML3}	L_{out}
Dichloromethane	11.0	6.0	4.5	2.3	0.5
Chloroform	6.4	1.9	0.8	0.6	0.7
1,1,1-Trichloroethane	2.9	ND	ND	ND	0.2
Trichloroethylene	6.9	ND	0.4	0.3	0.1
Tetrachloroethylene	15.1	3.7	7.0	5.1	1.2
1,4-Dichlorobenzene	ND	ND	ND	ND	0.5
Toluene	10.5	ND	0.5	0.6	0.1
p-Xylene	36.5	2.6	0.6	0.2	0.1
4-Ethyl Toluene	50.2	0.3	0.4	ND	1.2
1,3,5-Trimethylbenzene	33.7	3.5	0.1	0.6	0.7

Table 3.29- The Mean Percent Removal of The Candidate VOCs Observed At The Burlington Skyway Full Scale Aeration Basin and The Removal Observed During Pilot Plant Experiments (Burlington Skyway Wastewater, 5 day SRT)

	Full Scale Basin		Pilot Plant
	Exper #1	Exper #2	Average
	Mean Percentage Removal		
Dichloromethane	80	95	73
Chloroform	66	89	69
1,1,1-Trichloroethane	60	93	79
Trichloroethylene	94	98	88
Tetrachloroethylene	94	92	88
1,4-Dichlorobenzene	42	*--	77
Toluene	98	>99	94
p-Xylene	**74	>99	95
4-Ethyl Toluene	>99	98	>99
1,3,5-Trimethylbenzene	98	98	>99

*- negative number, very low influent concentration
**- analytical laboratory had high blank concentration

Table 3.30-Comparing Candidate VOC Removals Observed At The Burlington Skyway Full Scale Aeration Basin To Those Observed In The Pilot Plant (5 day SRT)

Null Hypothesis: Percentage Removals Are Equal In The Pilot Plant and The Full Scale Aeration Basin

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Full Scale		Pilot Plant				
Number of Experiments	2		8				
	Percentage Removal				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	88	11	74	11	125	-1.54	0.16
1,4-Dichlorobenzene	78	16	70	22	454	-0.47	0.65
1,1,1-Trichloroethane	77	23	79	20	412	0.12	0.90
Trichloroethylene	88	10	96	3	82	-1.09	0.30
Tetrachloroethylene	93	1	88	8	61	-0.81	0.44
Toluene	99	2	94	25	323	-1.02	0.27
4-Ethyl Toluene	98	6	99	8	111	0.22	0.85
1,3,5-Trimethylbenzene	98	4	99	7	97	0.31	0.82

percentage removal of the VOCs from the pilot plant and from full scale aeration basin. This suggests that the pilot plant represented full scale operating conditions.

For each VOC, the gas-liquid phase partitioning coefficient at each aeration basin sampling location was defined as the ratio of the measured off-gas concentration to the mixed liquor concentration (C_{og}/C_{ML}). Fractional saturation was defined as (C_{og}/C_{ML}) divided by the Henry's Law coefficient (H). Table 3.31 presents the average fractional saturations ((C_{og}/C_{ef})/H) of the candidate VOCs measured at each sampling location. Toluene is not included in Table 3.31 because high off-gas blank concentrations were still being recorded. Henry's Law constants were not available for 4-ethyl toluene and 1,3,5-trimethylbenzene. The data in Table 3.31 are very inconsistent, and the gas-liquid phase partitioning observed in the full scale aeration basin does not correspond well to that observed previously in the pilot plant (Table 3.25). However, sampling of the full scale aeration basin took place during sunny, hot (> 35 °C) weather, and the off-gas sampling chambers were not shaded. Most likely, the off-gas sampling cartridges became quite hot, inhibiting the adsorption of some VOCs on the Tenax. The measured fractional saturations of tetrachloroethylene and trichloroethylene were especially low suggesting that the adsorption of these VOCs was severely inhibited.

3.4 Highland Creek Wastewater Results

3.4.1 Pilot Plant Non-Dosed Wastewater Experiments; 5 day SRT

Six pilot plant non-dosed wastewater experiments were performed using wastewater from the Highland Creek WPCP. Three pilot plant experiments were also performed in which simultaneous sampling of a Highland Creek WPCP aeration basin was carried out.

Table 3.31- VOC Gas-Liquid Phase Partitioning At Burlington Skyway Full Scale Aeration Basin

Location	1	2	3	Avg
Experiment Number 1				
	Fractional Saturation			
Dichloromethane	1.0	1.4	0.3	0.9
Chloroform	0.8	0.3	0.2	0.4
1,1,1-Trichloroethane	0.2	0.2	0.1	0.1
Trichloroethylene	0.0	0.0	0.0	0.0
Tetrachloroethylene	0.0	0.0	0.0	0.0
1,4-Dichlorobenzene	0.7	1.0	0.3	0.7
p-Xylene	1.2	2.4	0.3	1.3
Experiment Number 2				
Dichloromethane	2.5	**---	0.3	1.4
Chloroform	0.5	**---	1.0	0.7
1,1,1-Trichloroethane	*---	**---	*---	---
Trichloroethylene	*---	**---	0.2	---
Tetrachloroethylene	0.2	**---	0.1	0.2
1,4-Dichlorobenzene	*---	**---	*---	---
p-Xylene	1.3	**---	0.2	0.8

*- concentration in mixed liquor reported as ND

**- data discarded because of error in off-gas sample analysis

The pilot plant experimental conditions are summarized in Table 3.32. A comparison of the pilot plant and full scale aeration basin sampling results is presented in Section 3.4.2. All 10 candidate VOCs were observed in the pilot plant influent. Influent concentrations of dichloromethane, 1,1,1-trichloroethane and toluene were consistently high, frequently approaching 300 µg/L. The influent concentration of trichloroethylene was frequently less than 2 µg/L. The influent concentrations of the remaining 6 candidate VOCs generally ranged from 2-15 µg/L.

For each experiment the concentration and mass flowrate of each candidate VOC in the pilot plant influent, effluent, waste activated sludge and off-gas was calculated. The VOC concentrations of influent and effluent samples taken at the beginning and end of the off-gas sampling interval were averaged to obtain a single influent and effluent concentration for each VOC. If duplicate off-gas sampling cartridges were analyzed, these concentration measurements were also averaged to obtain a single off-gas concentration for each VOC. The VOC concentration data from the Highland Creek non-dosed wastewater experiments are contained in Appendix A.6.

3.4.1.1 Mass Balance Closure

The mass balance closure for each VOC was defined as in Section 3.3.1.1. As noted during experiments using Burlington Skyway wastewater, measured concentrations of the candidate VOCs in the waste activated sludge were not significantly higher than those observed in the effluent. The concentration of the VOCs measured in the waste activated sludge and effluent are presented in Appendix A. Again, because the volume of sludge wasted daily to maintain a 5 day SRT is much less than the effluent flow, sorption on the waste activated sludge was not a major VOC removal

Table 3.32-Non-Dosed Wastewater Pilot Plant Experiments (Highland Creek Wastewater)

Experiment Number	Diffuser Bubble Type	Airflow Rate (m^3/m^3min)	Oxygen $\alpha K_L aV/Q_g$	Mixed Liquor Temperature (°C)
No Simultaneous Full Scale Sampling				
II.C.1.1	Fine	0.04	2.2	23.5
II.C.1.2	Coarse	0.16	1.1	23.0
II.C.1.3	Coarse	0.05	1.1	20.5
II.C.1.4	Coarse	0.16	1.1	19.5
II.C.1.5	Fine	0.12	2.2	17.5
II.C.1.6	Coarse	0.05	1.1	18.5
Simultaneous Full Scale Sampling				
II.C.2.1	Fine	0.04	2.2	19.0
II.C.2.2	Fine	0.04	2.2	19.0
II.C.2.3	Fine	0.04	2.2	19.0

mechanism.

The mass balance closure of each candidate VOC for each experiment is shown in Table 3.33. The average mass balance closures for toluene, p-Xylene, 4-ethyl Toluene and 1,3,5-trimethylbenzene were below 10%, and well below those values observed during dosed tap water experiments (Table 3.8), suggesting substantial biological removal of these compounds. The average mass balance closure for the remaining 6 VOCs ranged from 25% to 107%. These mass balance closures were lower than those values observed during dosed tap water experiments (Table 3.8) suggesting a limited amount of biological removal of these VOCs.

Mass balance closures achieved using Highland Creek wastewater as the pilot plant influent were compared to mass balance closures during dosed tap water experiments using T-tests presented in Table 3.34. For p-xylene, 4-ethyl toluene, 1,3,5-trimethylbenzene, toluene, dichloromethane, trichloroethylene and 1,1,1-trichloroethane there was strong indication (null hypothesis: no difference in mass balance closure; $P < 0.01$) that mass balance closures were lower during wastewater experiments confirming that biological removal of these VOCs occurred. For chloroform, 1,4-dichlorobenzene and tetrachloroethylene there was less indication ($0.14 < P < 0.49$) that mass balance closures were lower during wastewater experiments suggesting less biological removal of these VOCs.

Mass balance closures achieved using Highland Creek wastewater as the pilot plant influent were compared to mass balance closures achieved with Burlington Skyway wastewater using T-tests presented in Table 3.35. For trichloroethylene and dichloromethane there was indication (null hypothesis: equal mass balance closures; $0.02 < P < 0.04$) that mass balance closures were lower using Highland Creek wastewater. Regularly observed concentrations of these compounds in the primary effluent of the Burlington Skyway and

Table 3.33-Mass Balance Closure of The Candidate VOCs (Pilot Plant Experiments Using Highland Creek Wastewater)

Experiment Number	1	2	3	4	5	6	7	8	9	Avg	Std Dev
	Mass Balance Closure										
Tetrachloroethylene	72	39	105	104	104	127	190	110	112	107	41
1,4-Dichlorobenzene	60	99	53	124	91	104	69	61	73	81	24
Trichloroethylene	19	*--	11	65	26	22	31	12	17	25	17
Chloroform	26	26	48	81	63	98	33	52	61	54	25
1,1,1-Trichloroethane	23	43	37	65	58	56	39	30	33	42	14
Dichloromethane	12	97	36	34	33	30	19	7	31	33	26
p-Xylene	4	13	4	12	6	2	2	2	2	5	4
4-Ethyl Toluene	2	3	2	12	12	2	2	2	2	4	4
Toluene	1	4	1	14	8	5	2	3	2	4	3
1,3,5-Trimethylbenzene	3	3	3	18	9	4	4	1	3	5	5

*- data discarded because of error in liquid sample analysis

Table 3.34-Comparing VOC Mass Balance Closures During Wastewater Experiments (Highland Creek Wastewater, 5 day SRT) To Mass Balance Closures During Dosed Tap Water Experiments

Null Hypothesis: Mass Balance Closures Are Equal For Tap Water and Wastewater Experiments

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Wastewater		Dosed Tap Water				
Number of Experiments	9		8				
	Mass Balance Closure				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	107	41	123	54	2230	-0.69	0.49
1,4-Dichlorobenzene	81	24	97	22	542	-1.35	0.19
Trichloroethylene	25	17	68	26	492	-3.87	0.00
Chloroform	54	25	76	34	862	-1.54	0.14
1,1,1-Trichloroethane	42	14	86	38	795	-3.12	0.01
Dichloromethane	33	26	103	31	826	-5.04	0.00
Toluene	4	4	67	8	39	-20.22	0.00
p-Xylene	5	4	74	15	157	-10.66	0.00
4-Ethyl Toluene	4	4	76	21	215	-10.08	0.00
1,3,5-Trimethylbenzene	5	5	70	15	114	-12.49	0.00

Table 3.35-Comparing VOC Mass Balance Closures During Pilot Plant Experiments Using Highland Creek Wastewater To Mass Balance Closures During Pilot Plant Experiments Using Burlington Skyway Wastewater (5 day SRT)

Null Hypothesis: Mass Balance Closures Are Equal For Experiments Employing Highland Creek and Burlington Skyway Wastewater

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

	Highland Creek Wastewater		Burl. Skyway Wastewater				
Number of Experiments	9		10				
	Mass Balance Closure				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	107	41	102	53	2512	0.08	0.94
1,4-Dichlorobenzene	82	24	92	26	636	-1.01	0.33
Trichloroethylene	25	17	70	42	1199	-2.67	0.02
Chloroform	54	25	67	31	832	-1.24	0.23
1,1,1-Trichloroethane	43	14	55	36	725	-0.65	0.52
Dichloromethane	33	26	55	27	684	-2.25	0.04
p-Xylene	5	4	8	12	44	-0.82	0.42
4-Ethyl Toluene	4	4	3	1	11	1.60	0.14
1,3,5-Trimethylbenzene	5	5	4	3	18	0.58	0.57

Highland Creek WPCPs were not substantially different (i.e.. < 5 µg/L for trichloroethylene and > 75 µg/L for dichloromethane), suggesting that the lower mass balance closures observed at Highland Creek were not due to acclimation. Perhaps the greater pilot plant MLSS concentration (3.3 g/L versus 2.2 g/L) observed when Highland Creek wastewater was the feed source increased the biological removal of these 2 VOCs. For the remaining VOCs there was little indication ($0.14 < P < 0.94$) of a difference in the mass balance closures achieved using the different wastewater sources. Twelve volatiles, other than the candidate ten, included on the MOE Effluent Monitoring Priority Pollutant list (Ontario Ministry of Environment, 1988a) were observed in the pilot plant influent. Mass balance closures for these VOCs are summarized in Table 3.36. For 11 of the 12 compounds, the average mass balance closure was less than 10% suggesting substantial biological removal of these compounds. The average mass balance closure for 1,1-dichloroethane (the only non-candidate halogenated compound detected) was 30% suggesting incomplete biological removal of this compound. Thus, as observed during experimentation with Burlington Skyway WPCP wastewater, the 15 VOCs displaying extensive biological removal (4 candidate VOCs plus 11 non-candidate VOCs) were all non-halogenated alkylaromatic organics.

3.4.1.2 Gas-Liquid Phase Partitioning and Diffuser Type

For each VOC, the gas-liquid phase partition coefficient (C_{og}/C_{ef}) observed in the pilot plant was defined as in Section 3.2.2. Table 3.37 presents the average C_{og}/C_{ef} of each candidate VOC for experiments employing the coarse or fine bubble diffusers. For toluene, p-xylene, 4-ethyl toluene, and 1,3,5-trimethylbenzene the effluent concentrations were generally below the analytical detection limits because of extensive biological removal and C_{og}/C_{ef}

Table 3.36-Mass Balance Closures of The Non-Candidate VOCs; Pilot Plant Experiments Using Highland Creek Wastewater

	Mass Balance Closure (%)
Ethyl Benzene	< 10
m-Xylene	< 10
o-Xylene	< 10
Propyl Benzene	< 10
Isopropyl Benzene	< 10
2-Ethyl Toluene	< 10
3-Ethyl Toluene	< 10
1,2,3-Trimethylbenzene	< 10
1,2,4-Trimethylbenzene	< 10
1.3-Diethylbenzene	< 10
1,4-Diethylbenzene	< 10
1,1-Dichloroethane	30

Table 3.37-The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}); Pilot Plant Experiments Using Highland Creek Wastewater

Diffuser Type	Coarse Bubble	Fine Bubble
Oxygen $\alpha K_L aV/Q_g$	1.1	2.2
Number of Experiments	4	5
	C_{og}/C_{ef} (ng/L/µg/L)	
Dichloromethane	142	127
Chloroform	74	85
1,1,1-Trichloroethane	287	295
Tetrachloroethylene	600	611
1,4-Dichlorobenzene	135	179

is not reported for these VOCs. For trichloroethylene, effluent concentrations were also generally below the analytical detection limit because of low influent concentrations and C_{eg}/C_{ef} is also not reported for this VOC. As observed earlier at the Burlington Skyway site, the VOCs displaying the greatest gas-phase partitioning were tetrachloroethylene and 1,1,1-trichloroethane which also had the highest reported Henry's Law coefficients.

The effect of diffuser type on gas-liquid phase partitioning of the VOCs was examined using T-tests presented in Table 3.38. For 4 of the 5 compounds examined there was little indication (null hypothesis: no effect of diffuser type; $0.47 < P < 0.97$) that the diffuser type affected the gas-liquid phase partitioning of the VOCs. For 1,4-dichlorobenzene there was some indication ($P = 0.05$) that gas phase partitioning was higher with the fine bubble diffuser system. Thus, if the result for 1,4-dichlorobenzene is accepted as anomalous, there is little indication that the greater gas-liquid phase mass transfer efficiency of the fine bubble diffusers (indicated by the greater oxygen K_LaV/Q_g) increased the gas phase partitioning of the VOCs. This suggests that equilibrium existed between the VOC gas and liquid phases with both diffuser types.

Fractional saturation of the VOCs was defined as in section 3.2.2. Table 3.39 presents the average observed fractional saturation for the pilot plant experiments employing Highland Creek wastewater at a mixed liquor temperature within 2 °C of 20 °C. The average fractional saturations ranged from 0.5 to 1.4, and as observed when Burlington Skyway was the pilot plant influent (Table 3.25), fractional saturations were highest for 1,4-dichlorobenzene and 1,1,1-trichloroethane and were lowest for chloroform and tetrachloroethylene.

Fractional saturations observed using Highland Creek wastewater as the pilot plant influent were compared to those

Table 3.38- Testing the Effect of Diffuser Type On The Ratio of VOC Off-gas To Effluent Concentration (C_{og}/C_{ef}); Pilot Plant Experiments Using Highland Creek Wastewater

Null Hypothesis: No effect of diffuser type on C_{og}/C_{ef}

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Coarse Bubble		Fine Bubble				
Number of Experiments	4		5				
Oxygen $\alpha K_L aV/Q_g$	1.1		2.2				
	C_{og}/C_{ef} (ng/L/µg/L)				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	142	31	127	27	828	0.76	0.47
Chloroform	74	27	85	17	526	-0.62	0.55
1,1,1-Trichloroethane	287	44	295	102	6831	-0.13	0.90
Tetrachloroethylene	600	86	611	369	104084	-0.04	0.97
1,4-Dichlorobenzene	135	37	179	18	763	-2.37	0.05

Table 3.39-Observed VOC Fractional Saturation ($((C_{og}/C_{ef})/H)$; Pilot Plant Experiments Using Highland Creek Wastewater

		$(C_{og}/C_{ef})/H$	
	H	Avg.	Std Dev
Dichloromethane	130	1.1	0.2
Chloroform	140	0.6	0.1
1,1,1-Trichloroethane	200	1.4	0.5
Tetrachloroethylene	1190	0.5	0.3
1,4-Dichlorobenzene	110	1.4	0.3

observed during dosed tap water experiments using T-tests presented in Table 3.40. For four of the five VOCs examined there was no indication (null hypothesis: no difference in fractional saturation; $0.11 < P < 0.96$) of a difference in fractional saturation of the VOCs between the wastewater and tap water experiments. For dichloromethane there was indication ($P = 0.01$) that gas phase partitioning was greater during the wastewater experiments. This result is likely anomalous because gas-liquid phase mass transfer efficiency, indicated by oxygen $\alpha K_L aV/Q_G$, was greater during tap water experimentation. Certainly, there is no indication that the greater gas-liquid mass transfer efficiency of the tap water experiments increased the gas phase partitioning of the VOCs. This suggests that equilibrium existed between the VOC gas and liquid phases over the range of mass transfer conditions examined even though the gas phase concentrations differed from Henry's Law predictions.

3.4.1.3 Airflow Rate and Percentage Stripped

The percentage of each VOC stripped from the aeration basin was defined as in Section 3.2.2. Table 3.41 lists the Highland Creek pilot plant experiments from left to right in order of increasing airflow rate, and, for a given airflow rate, lists the average percentage stripped of each VOC. No distinction was made between diffuser types in Table 3.41 because there was little evidence of an effect of diffuser type on the partitioning of the VOCs between the gas and liquid phases. As observed during Burlington Skyway experimentation (Table 3.25), the VOCs displaying the greatest amount of stripping were tetrachloroethylene and 1,4 dichlorobenzene. Compounds stripped the least, due to competing biological removal, were toluene, 4-ethyl toluene, p-xylene and 1,3,5-trimethylbenzene. Trichloroethylene appeared to be stripped

Table 3.40- Comparing VOC Fractional Saturation ($(C_{eq}/C_{ef})/H$) Observed During Pilot Plant Experiments Using Highland Creek Wastewater Experiments To That Observed During Tap Water Experiments

Null Hypothesis: No change in fractional saturation

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

	Wastewater	Tap Water
Range of Oxygen $K_L aV/Q_g$	1.1-2.2	2.2-4.5
Number of Experiments	6	2

	Fractional Saturation				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Dichloromethane	1.11	0.21	0.48	0.06	0.04	-3.99	0.01
Chloroform	0.63	0.10	0.62	0.04	0.01	-0.15	0.88
1,1,1-Trichloroethane	1.45	0.47	1.37	0.64	0.25	-0.19	0.85
Tetrachloroethylene	0.52	0.07	0.52	0.07	0.05	-0.05	0.96
1,4-Dichlorobenzene	1.42	0.31	1.00	0.06	0.08	-1.83	0.11

Table 3.41-Percentage of The Influent Mass Flow of The Candidate VOCs Stripped and Airflow Rate (Pilot Plant Experiments Using Highland Creek Wastewater)

Number of Experiments	4	2	1	2	
Airflow Rate (m^3/m^{3}min)	0.04	0.05	0.12	0.16	
	Percentage Stripped				Avg
Tetrachlorethylene	108.0	106.0	103.0	71.4	99
1,4-Dichlorobenzene	48.1	56.8	80.2	95.5	64
Trichloroethylene	19.5	15.9	26.1	8.7	17
Chloroform	24.1	46.4	48.4	43.8	36
1,1,1-Trichloroethane	24.8	39.3	54.3	51.4	37
Dichloromethane	11.4	23.9	27.7	57.4	26
Toluene	2.1	2.9	7.7	8.8	4
p-Xylene	2.3	3.8	5.9	8.1	4
4-Ethyl Toluene	2.1	2.1	6.3	8.1	4
1,3,5-Trimethylbenzene	2.9	4.0	9.1	10.8	6
Average	25	31	37	36	

less at the Highland Creek site possibly due to increased biological removal as discussed in Section 3.4.1.2. Scanning Table 3.41 from left to right reveals that the percentage stripped generally increased with increasing airflow rate, but the relative increase in percentage stripped was less than the relative increase in airflow rate. At airflow rates below 0.05 m^3/m^3min, less than 5% of the influent mass flow of the non-chlorinated aromatics was stripped from the aeration basin.

3.4.2 Parallel Pilot Plant/Full Scale Aeration Basin Experiments

Three parallel pilot plant/full scale aeration basin experiments were carried out at the Highland Creek WPCP. Off-gas and mixed liquor samples were taken at the influent, mid-way and at the end of the full scale aeration basin (Figure 2.3). The influent to the full scale aeration basin and the effluent from the full scale secondary settlers were also sampled. The pilot plant influent, effluent and off-gas were sampled simultaneously with the full scale aeration basin sampling. VOC concentration measurements from mixed liquor samples taken at the beginning and end of the off-gas sampling interval were averaged to obtain a single mixed liquor concentration for each VOC for each sample location. All VOC concentration data collected in the parallel pilot plant/Highland Creek full scale aeration basin experiments are presented in Appendix A.7.

3.4.2.1 Removal of VOCs

Table 3.42 summarizes the concentration of the candidate VOCs in the influent to the full scale aeration basin and in the mixed liquor and off-gas at sampling locations 1,2 and 3 (Figure 2.3) for a typical experiment. The mixed liquor and off-gas concentrations of toluene, p-Xylene, 4-ethyl toluene, and 1,3,5-trimethylbenzene measured in the aeration basin were much lower than could be

Table 3.42- Typical Variation in Candidate VOC Concentration Along The Length of The Full Scale Highland Creek Aeration Basin

	L_{in}	L_{ML1}	L_{ML2}	L_{ML3}	G_{ML1}	G_{ML2}	G_{ML3}
	Concentration (µg/L)				Concentration (ng/L)		
Tetrachloroethylene	5.5	1.3	0.9	0.8	1087	771	792
1,4-Dichlorobenzene	4.8	1.4	1.3	1.2	241	134	158
Trichloroethylene	1.0	ND	ND	ND	35	15	9
Chloroform	2.7	0.7	0.5	0.5	58	32	29
1,1,1-Trichloroethane	226.3	48.7	24.0	24.5	6588	3950	3682
Dichloromethane	32.7	5.2	2.5	2.4	460	196	152
p-Xylene	41.5	0.5	ND	ND	225	28	15
Toluene	121.0	ND	ND	ND	*--	*--	*--
4-Ethyl Toluene	18.6	0.1	ND	ND	56	8	ND
1,3,5-Trimethylbenzene	9.0	ND	ND	ND	43	8	ND

*- data discarded because of high off-gas blank concentrations

accounted for by stripping alone suggesting substantial biological removal of these VOCs. The mixed liquor and off-gas concentrations of the remaining 6 VOCs decreased moderately along the length of the aeration basin. This moderate decrease in concentration along the length of the aeration basin suggests that the aeration tank contents were not as completely mixed as the hydraulic study indicated (Figure 2.11).

The mean percentage removal of each VOC from the pilot plant and full scale aeration basin was defined as:

$\%\ \text{Removal} = [1-(C_e/C_i)]*100$ ....(3.1)

C_e = aeration basin effluent VOC concentration
C_i = aeration basin influent concentration.

Table 3.43 presents the influent concentration, effluent concentration and mean percentage removal of each candidate VOC observed in the pilot plant and the full scale aeration basin for each of the three parallel experiments. In most cases, the influent concentration to the pilot plant exceeded the influent concentration to the full scale aeration basin suggesting that volatilization of VOCs occurred in the channel leading from the primary settlers to the full scale aeration basin. The removals of p-xylene, toluene, 4-ethyl toluene, and 1,3,5-trimethylbenzene consistently exceeded 99% because of extensive biological removal. The removal of trichloroethylene was also consistently high possibly because of extensive biological removal. The removals of the other VOCs ranged from 73% to 95%. Removals in the pilot plant and the full scale aeration basin were compared using T-tests presented in Table 3.44. For six compounds there was no indication (null hypothesis: no difference in removal; $P = 1.00$) of a difference in removal of the VOCs between the pilot plant and the full scale aeration basin. For tetrachloroethylene and 1,1,1-trichloroethane there was little indication ($0.39 < P < 0.72$) of a difference in removals from the pilot plant and the full scale

Table 3.43- Mean Percentage Removal of The Candidate VOCs (Parallel Pilot Plant/Highland Creek Full Scale Aeration Basin Experiments)

	Pilot Plant			Full Scale		
	Inf Conc (µg/L)	Eff Conc (µg/L)	Removal (%)	Inf Conc (µg/L)	Eff Conc (µg/L)	Removal (%)
Experiment 1						
Tetrachloroethylene	6.7	0.7	90	5.5	0.8	85
1,4-Dichlorobenzene	5.3	1.0	81	4.8	1.2	75
Trichloroethylene	1.4	ND	>90	1.1	ND	>90
Chloroform	3.8	0.5	87	2.7	0.5	82
1,1,1-Trichloroethane	237.0	11.6	95	226.3	24.5	89
Dichloromethane	46.6	2.5	95	32.7	2.4	93
p-Xylene	42.8	ND	>99	37.8	ND	>99
Toluene	150.5	ND	>99	121.0	ND	>99
4-Ethyl Toluene	19.7	ND	>99	18.6	0.1	99
1,3,5-Trimethylbenzene	9.6	ND	>99	9.0	ND	>99
Experiment 2						
Tetrachloroethylene	1.3	0.2	85	0.5	0.2	60
1,4-Dichlorobenzene	4.3	0.7	84	4.3	1.0	75
Trichloroethylene	14.1	ND	>99	10.3	0.3	97
Chloroform	3.1	0.7	77	2.5	0.6	76
1,1,1-Trichloroethane	148.5	9.1	94	119.4	11.4	90
Dichloromethane	129.9	3.3	97	66.9	1.4	98
p-Xylene	11.9	ND	>99	9.8	ND	>99
Toluene	320.0	ND	>99	240.0	0.1	>99
4-Ethyl Toluene	7.8	ND	>99	6.9	ND	>99
1,3,5-Trimethylbenzene	3.9	ND	>99	3.3	ND	>99
Experiment 3						
Tetrachloroethylene	13.9	2.2	84	8.2	1.0	88
1,4-Dichlorobenzene	4.6	0.9	80	4.3	1.2	73
Trichloroethylene	1.8	ND	>90	1.3	ND	>90
Chloroform	3.1	0.9	80	2.6	0.4	86
1,1,1-Trichloroethane	131.2	10.6	92	121.0	9.5	92
Dichloromethane	41.5	4.3	90	21.8	1.3	94
p-Xylene	15.0	ND	>99	15.4	ND	>99
Toluene	86.1	ND	>99	50.4	ND	>99
4-Ethyl Toluene	14.1	ND	>99	15.2	ND	>99
1,3,5-Trimethylbenzene	6.7	ND	>99	6.8	ND	>99

Table 3.44-Comparing VOC Removal Observed In The Pilot Plant and in The Full Scale Aeration Basin During Parallel Pilot Plant/Highland Creek Full Scale Aeration Basin Experiments

Null Hypothesis: Removals Are Equal In The Pilot Plant and The Full Scale Aeration Basin

Reject Null Hypothesis at 95 % Confidence Level if P <0.05

	Pilot Plant		Full Scale				
Number of Experiments	3		3				
	Removal Percentage				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	86	3	78	15	123	0.95	0.39
1,4-Dichlorobenzene	82	2	74	1	3	5.33	0.01
Trichloroethylene	>90	0	>90	0	0	0.00	1.00
Chloroform	81	5	81	5	26	0.00	1.00
1,1,1-Trichloroethane	94	2	90	2	2	2.67	0.06
Dichloromethane	94	4	95	3	10	-0.38	0.72
Toluene	>99	0	>99	0	0	0.00	1.00
p-Xylene	>99	0	>99	0	0	0.00	1.00
4-Ethyl Toluene	>99	0	>99	0	0	0.00	1.00
1,3,5-Trimethylbenzene	>99	0	>99	0	0	0.00	1.00

aeration basin. For 1,4-dichlorobenzene and 1,1,1-trichloroethane there was indication ($0.01 < P < 0.06$) of greater removal in the pilot plant, but the absolute difference in removal for these compounds was less than 8%. Thus, generally, removal of the VOCs in the pilot plant were very similar to those in the full scale aeration basin suggesting that the pilot plant adequately represented full scale operating conditions.

3.4.2.2 Gas-Liquid Phase Partitioning

In the full scale aeration basin, the gas-liquid partitioning coefficient of each VOC at each off-gas sampling location was defined as the ratio of the measured off-gas concentration to the mixed liquor concentration (C_{og}/C_{ML}). Fractional saturation was defined as C_{og}/C_{ML} divided by the reported Henry's Law coefficient (H). For the pilot plant, fractional saturation was defined as the ratio of the off-gas to the effluent concentration (C_{og}/C_{ef}) divided by the reported Henry's Law coefficient.

Table 3.45 summarizes the fractional saturation of the candidate VOCs observed in the pilot plant and the full scale aeration basin for each parallel experiment. The mixed liquor and effluent concentrations of trichloroethylene, toluene, 4-ethyl toluene, p-xylene and 1,3,5-trimethylbenzene were frequently below the analytical detection limit, and these VOCs are not included in Table 3.45. As repeatedly observed earlier, the compounds displaying the highest fractional saturation were 1,4-dichlorobenzene and 1,1,1-trichloroethane while the compounds displaying the lowest fractional saturations were tetrachloroethylene and chloroform.

Table 3.46 compares the fractional saturations observed in the pilot plant to those observed in the full scale aeration basin using T-tests. For four of the 5 VOCs there was little indication (null hypothesis: no difference; $0.22 < P < 0.75$), of a difference

Table 3.45- Fractional Saturation of Candidate VOCs in The Pilot Plant and The Full Scale Aeration Basin (Parallel Pilot Plant/Highland Creek Full Scale Aeration Basin Experiments)

	Pilot Plant	Full Scale		
		Loc #1	Loc# 2	Loc #3
Oxygen $\alpha K_L aV/Qg$	2.2	3.5	3.5	3.5
	Fractional Saturation			
Experiment #1				
Dichloromethane	1.3	0.7	0.6	0.5
Chloroform	0.8	0.6	0.5	0.4
1,1,1-Trichloroethane	2.3	0.7	0.7	0.7
Tetrachloroethylene	1.0	0.7	0.7	0.8
1,4-Dichlorobenzene	1.6	1.6	0.9	1.2
Experiment #2				
Dichloromethane	0.8	0.6	0.6	0.6
Chloroform	0.6	0.7	0.6	0.4
1,1,1-Trichloroethane	1.2	1.3	1.5	1.3
Tetrachloroethylene	0.3	0.4	0.3	0.3
1,4-Dichlorobenzene	1.6	1.7	1.3	1.7
Experiment #3				
Dichloromethane	1.0	0.6	0.6	0.6
Chloroform	0.5	0.7	0.6	0.4
1,1,1-Trichloroethane	1.0	1.1	1.5	1.3
Tetrachloroethylene	0.3	0.5	0.3	0.3
1,4-Dichlorobenzene	1.7	1.7	1.3	1.7

Table 3.46-Comparing VOC Fractional Saturation Observed In The Pilot Plant and The Full Scale Aeration Basin (Parallel Pilot Plant/Highland Creek Full Scale Aeration Basin Experiments)

Null Hypothesis: Fractional Saturations Are Equal In The Pilot Plant and The Full Scale Aeration Basin

Reject Null Hypothesis at 95 % Confidence Level if $P < 0.05$

	Pilot Plant		Full Scale				
Number of Data Points	3		9				
Oxygen $\alpha K_L aV/Q_a$	2.2		3.5				
	Fractional Saturation				pooled variance	test statistic	Null Hypothesis P-value
	Avg	Std Dev	Avg	Std Dev			
Tetrachloroethylene	0.53	0.40	0.47	0.20	0.07	0.32	0.75
1,4-Dichlorobenzene	1.63	0.06	1.46	0.29	0.07	1.02	0.34
Chloroform	0.63	0.15	0.54	0.12	0.01	1.02	0.33
1,1,1-Trichloroethane	1.50	0.70	1.12	0.34	0.18	1.30	0.22
Dichloromethane	1.03	0.25	0.60	0.05	0.01	5.36	0.01

in fractional saturation between the pilot plant and the full scale aeration basin. For dichloromethane there was indication ($P = 0.01$) that fractional saturation was greater in the pilot plant. This result is likely anomalous because gas-liquid phase mass transfer efficiency, indicated by oxygen $\alpha K_L aV/Q_g$, was greater in the full scale aeration basin. Certainly, there is no indication that the greater gas-liquid phase mass transfer efficiency of the full scale aeration basin increased the gas phase partitioning of the VOCs. This suggests that equilibrium existed between the VOC gas and liquid phases over the range of mass transfer conditions examined even though the gas phase concentrations differed from Henry's Law predictions. The similarity of the VOC gas-liquid phase concentration coefficients ($C_{eg}/C_{e\ell}$) measured in the pilot plant and the full scale aeration basin also suggest that the pilot plant and full scale sampling protocols were equivalent.

4. SUMMARY OF RESULTS AND DISCUSSION

4.1 Mass Balance Closure

For each pilot plant experiment, the concentration and mass flowrate of each VOC in the influent, effluent, off-gas and waste activated sludge were calculated. For each VOC the mass balance closure was defined as the sum of the total measured effluent VOC mass flow plus the total measured off-gas VOC mass flow plus the measured waste sludge VOC mass flow all divided by the measured influent VOC mass flow. Sample mass balance closure calculations for tap water and wastewater experiments were presented in Tables 3.7 and 3.14.

The measured concentration of VOCs in the waste activated sludge were more variable than the effluent concentrations but not significantly higher. Since the volume of sludge wasted daily to maintain a 5 or 10 day SRT was much less than the effluent flow, sorption on the waste activated sludge was determined not to be a major VOC removal mechanism.

All the components of the mass balance (i.e. % stripped, % wasted, % in effluent), for each pilot plant experiment are presented in Appendix D. Table 4.1 summarizes the percentage mass balance closure of the 10 candidate VOCs for the dosed tap water experiments and for the wastewater experiments employing Burlington Skyway and Highland Creek wastewaters. Dosed tap water mass balance closures ranged from 67% to 123% suggesting acceptable sampling and analytical accuracy. Using Burlington wastewater at a 5 day SRT, the mass balance closures for toluene, 4-ethyl toluene, 1,3,5-trimethylbenzene, and p-xylene were 8% or less and the closures were well below those values observed during dosed tap water experiments suggesting substantial biological removal of these VOCs. The mass balance closure for the remaining 6 compounds (which were all chlorinated compounds) ranged from 55% to 102% and

Table 4.1- VOC Mass Balance Closure Summary, Candidate VOCs

	Dosed Tap Water		Burl. Skyway Wastewater 5 day SRT		Burl. Skyway Wastewater 10 day SRT		Highland Cr. Wastewater 5 day SRT	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
	Mass Balance Closure (%)							
Trichloroethylene	68	26	70	42	67	28	25	17
Chloroform	76	34	67	31	46	9	54	25
1,1,1-Trichloroethane	85	35	55	36	56	16	42	14
1,4-Dichlorobenzene	96	20	92	26	67	27	81	24
Dichloromethane	103	29	55	27	57	20	33	26
Tetrachloroethylene	123	50	102	53	97	32	107	41
1,3,5-Trimethylbenzene	69	13	4	3	2	1	5	5
4-Ethyl Toluene	76	19	3	1	2	1	4	4
Toluene	67	7	*--	--	9	5	4	3
p-Xylene	74	14	8	12	3	2	5	4

* -data discarded because of high off-gas blank concentration

were moderately lower than those observed during dosed tap water experiments suggesting limited biological removal of these VOCs. Generally, mass balance closures at a 10 day SRT were not substantially lower than those observed at a 5 day SRT. However, the experiments were not explicitly designed to examine the effect of SRT and confounding variables (especially the difference in airflow rate between experiments) may have concealed an effect of SRT on the biological removal of the VOCs. A more sophisticated statistical analysis (involving a model accounting for the effect of airflow rate and non-linear parameter fitting) is required for a rigorous evaluation of the SRT effect on biological removal of the VOCs. Using Highland Creek wastewater, the mass balance closures of the non-chlorinated compounds were again below 10% suggesting consistent biological removal of these VOCs. Mass balance closures of trichloroethylene and dichloromethane were substantially lower at the Highland Creek site than at the Burlington Skyway site suggesting greater biological removal. Regularly observed influent concentrations of these compounds were not substantially different at the two sites discounting increased acclimation as a potential explanation for the greater biological removal observed at the Highland Creek site.

Table 4.2 lists the mass balance closure for 12 VOCs, other than the candidate 10, included on the MOE Effluent Monitoring Priority Pollutant List (Ontario Ministry of Environment, 1988a) observed in the Highland Creek or Burlington Skyway wastewater. Mass balance closures for all compounds except 1,1-dichloroethane were consistently below 10% suggesting significant biological removal of these non-chlorinated aromatic compounds. The average mass balance closure for 1,1-dichloroethane was 30% suggesting less biological removal than for the other non-candidate VOCs.

Of the candidate and non-candidate VOCs, the 7 VOCs that exhibited incomplete biological removal were either chlorinated

Table 4.2- VOC Mass Balance Closure Summary, Non-Candidate VOCs

	Mass Balance Closure (%)
Ethyl Benzene	< 10
m-Xylene	< 10
o-Xylene	< 10
Propyl Benzene	< 10
Isopropyl Benzene	< 10
2-Ethyl Toluene	< 10
3-Ethyl Toluene	< 10
1,2,3-Trimethylbenzene	< 10
1,2,4-Trimethylbenzene	< 10
1,3-Diethylbenzene	< 10
1,4-Diethylbenzene	< 10
1,1-Dichloroethane	30

aliphatics or chlorinated aromatics (Table 4.3). The 15 VOCs that exhibited extensive biological removal were non-chlorinated aromatics.

4.2 Gas-Liquid Phase Partitioning

For each pilot plant experiment, the average ratio of off-gas to effluent concentration (C_{og}/C_{ef}) of each candidate VOC was calculated. The effluent concentration represented the aeration basin contents concentration because the aeration basin contents were completely mixed. Thus, C_{og}/C_{ef} represents the observed partitioning coefficient between the VOC concentration in the gas phase to the VOC concentration in the liquid phase.

Table 4.4 presents the average gas phase partitioning constant for each VOC for each experimental condition. Also included in Table 4.4 is the Henry's Law constant reported in the literature for each VOC. For each experimental condition, it was concluded that the greater gas-liquid phase mass transfer efficiency of the fine bubble diffusers, indicated by the greater oxygen K_LaV/Q_g, did not increase the gas phase partitioning of the VOCs. Similarly, there was no indication that gas-phase partitioning of the VOCs was greater during tap water experiments (oxygen K_LaV/Q_g ranging from 2.2 for coarse bubble system to 4.5 for fine bubble) than during wastewater experiments (oxygen $\alpha K_LaV/Q_g$ ranging from approximately 1.1 for coarse bubble diffuser system to 2.2 for fine bubble diffuser system). Thus, across a range in oxygen KL_aV/Q_g of approximately 1.1 to 4.5 there was no indication of an increase in the gas phase partitioning of the VOCs with increasing gas-liquid phase mass transfer efficiency. This suggests that equilibrium existed between the gas and liquid phases during all experimental conditions although the observed gas-liquid phase partition constants differed from those predicted by Henry's Law. Thus, in

Table 4.3-VOC Biological Removal Summary

VOCs Exhibiting Limited Biological Removal
Tetrachloroethylene
1,4-Dichlorobenzene
Trichloroethylene
Chloroform
1,1,1-Trichloroethane
Dichloromethane
1,1-Dichloroethane
VOCs Exhibiting Significant Biological Removal
p-Xylene
Toluene
4-Ethyl Toluene
1,3,5-Trimethylbenzene
Ethyl benzene
m-Xylene
o-Xylene
Propyl benzene
Isopropyl benzene
2-Ethyl toluene
3-Ethyl Toluene
1,2,3-Trimethylbenzene
1,2,4-Trimethylbenzene
1,3-Diethylbenzene
1,4-Diethylbenzene

Table 4.4- Gas-Liquid Phase Partitioning of The VOCs Observed In The Pilot Plant

	Dosed Tap Water		Burl. Skyway Wastewater		Highland Cr. Wastewater	
	Coarse Bubble	Fine Bubble	Coarse Bubble	Fine Bubble	Coarse Bubble	Fine Bubble
	C_{eq}/C_{ef} ((ng/L)/(µg/L))					
Trichloroethylene	277	198	268	212	**--	**--
Chloroform	90	83	75	66	74	85
1,1,1-Trichloroethane	184	366	191	41	287	295
1,4-Dichlorobenzene	115	106	149	111	135	179
Dichloromethane	57	68	109	40	142	127
Tetrachloroethylene	554	673	443	493	600	611
1,3,5-Trimethylbenzene	*--	216	**--	**--	**--	**--
4-Ethyl Toluene	*--	263	**--	**--	**--	**--
Toluene	382	152	**--	**--	**--	**--
p-Xylene	*--	196	**--	**--	**--	**--

* - data discarded because of error in liquid sample analysis

** - effluent concentration was below the analytical detection limit full scale applications, the use of fine bubble diffusers with high oxygen transfer efficiencies would not increase the gas phase partitioning of the VOCs.

4.3 Airflow Rate and Percentage Stripped

The fraction of each VOC stripped from the pilot plant aeration basin was defined as the ratio of the measured VOC off-gas mass flow divided by the measured influent VOC mass flow. A sample calculation of percentage stripped is contained in Table 3.14.

In each experimental phase, pilot plant experiments were performed over a range of air flowrates. Table 4.5 presents typical results of the effect of air flowrate on the percentage of the influent mass flowrate of each VOC stripped from the aeration basin. In each experimental phase it was concluded that the percentage of each VOC stripped from the aeration basin increased with increasing air flowrate, but the relative increase in percentage stripped was less than the relative increase in air flowrate. At airflow rates of 0.05 m^3/m^3min or lower, less than 5% of the influent mass flow of p-xylene, toluene, 4-ethyl toluene and 1,3,5-trimethylbenzene was stripped from the aeration basin because of competing biological removal. However a substantial percentage of the influent mass flow of the remaining 6 candidate chlorinated compounds was stripped from the aeration basin at all airflow rates. Thus, in full scale applications, a reduction in airflow rate such as could be achieved with computerized DO control or the installation of more efficient diffuser systems (i.e. fine bubble diffusers that require less airflow to maintain adequate DO than coarse bubble diffusers) would minimize the stripping of VOCs. However a significant percentage of the chlorinated VOC mass flow entering the aeration basin would be stripped in any case.

Table 4.5- The Typical Effect of Airflow Rate On The Percentage of The Influent Mass Flow of Each Candidate VOC Stripped From The Pilot Plant Aeration Tank (Highland Creek Wastewater Experiments)

Number of Experiments	4	2	1	2	
Airflow Rate (m^3/m^3min)	0.04	0.05	0.12	0.16	
	Percentage Stripped				Avg
Tetrachlorethylene	108.0	106.0	103.0	71.4	99
1,4-Dichlorobenzene	48.1	56.8	80.2	95.5	64
Trichloroethylene	19.5	15.9	26.1	8.7	17
Chloroform	24.1	46.4	48.4	43.8	36
1,1,1-Trichloroethane	24.8	39.3	54.3	51.4	37
Dichloromethane	11.4	23.9	27.7	57.4	26
Toluene	2.1	2.9	7.7	8.8	4
p-Xylene	2.3	3.8	5.9	8.1	4
4-Ethyl Toluene	2.1	2.1	6.3	8.1	4
1,3,5-Trimethylbenzene	2.9	4.0	9.1	10.8	6
Average	25	31	37	36	

4.4 Phase I Report Complement

It was explained in Section 2.5.3 that the off-gas analysis calibration procedure was independently examined in Phase II. It was concluded that the original technique, used in Phase I, under estimated the VOC off-gas concentration by a factor ranging from 1.2 at high off-gas concentrations to 2.0 at low concentrations. Thus all off-gas concentration data in the Phase I report should be multiplied by a factor within this range. For total emissions, the correct multiplication factor is likely nearer 1.2 than 2.0 since most of the emissions were contributed by a few compounds at high concentrations. Accordingly, a factor of 1.35 (one quarter between 1.2 and 2.0) was selected to adjust emission estimates made in the Phase 1 report and the revised values are presented in Table 4.6.

With the revised off-gas analysis calibration procedure, the average mass balance closure for the pilot plant dosed tap water experiments ranged from 67% to 123% suggesting acceptable sampling and analytical accuracy. The gas-liquid phase partitioning of the VOCs observed in the pilot plant was similar to that observed in a Highland Creek full scale aeration basin during parallel pilot plant/full scale sampling experiments (Section 3.4.2.2) suggesting that the pilot plant and full scale sampling protocols were equivalent. Thus, since the pilot plant sampling protocol was shown to produce acceptable levels of accuracy and the pilot plant and full scale sampling protocols were shown to be equivalent, after adjustment for the revised off-gas analysis calibration procedure, the off-gas concentration and emission estimates contained in the Phase I report are considered to be acceptable.

Table 4.6- Revised Estimates of VOC Emissions From Full Scale Water Pollution Control Plants (Phase I)

	Total Estimated Emissions	
	Total (g/d)	Per Unit WW Vol. (g/$10^3$$m^3$)
Lakeview	6480	100
Highland Creek	5535	72
Skyway	3645	39
Waterloo	60	3

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1-Conclusions

The following conclusions are made as a result of this study:

1. Mass balance closures for 10 candidate VOCs during pilot plant dosed tap water experiments ranged from 67% to 123% suggesting acceptable sampling and analytical protocols. The pilot plant off-gas sampling protocol was shown to be equivalent to the full scale aeration basin off-gas sampling protocol used in the Phase I study.

2. In wastewater studies the pilot plant was able to match the oxygen transfer efficiency of the coarse bubble diffuser system at the Burlington Skyway WPCP. The pilot plant could achieve only 50% of the oxygen transfer efficiency of the fine bubble diffuser system at the Toronto Highland Creek WPCP in wastewater studies but could achieve it during dosed tap water experiments. Thus, the pilot plant spanned the range of gas-liquid phase mass transfer efficiency generally encountered in full scale plants.

3. In wastewater studies the pilot plant matched the conventional pollutant and VOC treatment efficiency of the Burlington Skyway and Toronto Highland Creek WPCPs.

4. With the pilot plant operated at a 5 and 10 day SRT, the loss of 15 non-chlorinated aromatic VOCs was attributed primarily to biological removal. Stripping removed less than 10% of the influent mass flowrate of these compounds.

5. In the same system, seven chlorinated aliphatic and aromatic compounds were not completely biologically removed and were discharged in the effluent and off-gas. Stripping was a major removal mechanism for these compounds.

6. There was no evidence that an increase in SRT from 5 to 10 days increased the biological removal of the VOCs. However, the experiments were not explicitly designed to examine the effect of SRT and confounding variables (especially the difference in airflow rate between experiments) may have concealed an effect. A more sophisticated statistical analysis (involving a model accounting for the airflow effect and non-linear parameter fitting) is required to rigorously evaluate the SRT effect.

7. Adsorption on to waste activated sludge was not a major removal mechanism for either the chlorinated or non-chlorinated VOCs, accounting for approximately one percent of VOC losses in the systems examined.

8. Under several experimental conditions, there was no evidence that the fine bubble diffuser system caused greater gas phase partitioning of the VOCs than did the coarse bubble diffuser system. Generally, there was no increase in gas-phase partitioning of the VOCs with increasing oxygen transfer efficiency. Hence, equilibrium apparently existed between the gas and liquid phases although the observed gas-liquid phase partition constants differed from the predicted Henry's Law values.

9. Stripping increased with increasing air flow rate, but the relative increase in percentage stripped was less than the relative increase in air flow rate. At airflow rates of 0.05 m^3/m^3min or lower, less than 5% of the influent mass flowrate of

the non-chlorinated aromatics was stripped from the aeration basin because of competing biological removal. A substantial percentage of the influent mass flowrate of the chlorinated compounds was stripped from the aeration basin at all airflow rates.

5.2-Recommendations

The following recommendations are made as a result of this study:

1. Computerized DO control and more efficient diffuser systems (e.g. fine bubble diffusers that require less airflow to maintain DO than coarse bubble systems) should be installed whenever possible to reduce airflow rates and hence minimize the stripping of VOCs at municipal wastewater treatment plants. Such measures would likely ensure that less than 5% of the influent mass flowrate of the non-chlorinated VOCs entering the aeration basin would be stripped. A significant percentage of the influent mass flowrate of the chlorinated VOCs would likely be stripped even under these optimal conditions.

2. Techniques for the measurement of VOC concentrations in air should be studied. A standard calibration procedure and a known confidence limit of accuracy should be established.

3. The effects of SRT, MLSS concentration and acclimation on the biological removal of VOCs should be investigated under controlled conditions. There was little evidence that increased SRT and MLSS concentration increased the biological removal of some VOCs but data variability was considerable.

4. The effect of mixed liquor temperature on Henry's Law coefficients and the rate of stripping of VOCs from aeration basins requires additional study.

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APPENDICES

N.B. The designation "ND" in all tables in the appendices means "not detected". The designation "NA" means not applicable.

APPENDIX A

Experimental Conditions and VOC Concentration Data

APPENDIX A.1 - EXPERIMENTAL CONDITIONS AND VOC CONCENTRATION DATA; DOSED TAP WATER PILOT-PLANT EXPERIMENTS

EXPERIMENTAL CONDITIONS:

EXPERIMENT NUMBER	DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
II-A.1	COARSE	16.0	4.80	29.0	8.5	1420
II-A.2	FINE	8.9	4.80	25.0	8.0	1335
II-A.3	FINE	3.5	4.80	20.0	9.0	745
II-A.4	COARSE	5.3	6.00	25.0	9.5	930
II-A.5	FINE	8.9	5.20	26.0	9.5	890
II-A.6	COARSE	5.3	4.70	23.0	10.2	875
II-A.7	COARSE	16.0	4.85	34.5	19.0	750
II-A.8	FINE	3.5	4.95	24.0	18.5	600

Table A1.1-VOC Concentration Data; Dosed Tap Water Experiment II-A.1

INFLUENT CONCENTRATION

Compound	S3 (t=25) (ug/L)	S4 (t=25) (ug/L)	S5 (t=26) (ug/L)	Avg (ug/L)
Dichloromethane	65.0	66.0	93.5	74.8
Chloroform	35.0	36.0	39.0	36.7
1,1,1-Trichloroethane	6.8	6.8	8.5	7.4
Trichloroethylene	24.0	24.0	29.0	25.7
Toluene	27.0	28.0	31.5	28.8
Tetrachloroethylene	3.6	3.3	3.9	3.6
p-Xylene	20.0	21.0	25.0	22.0
4-Ethyl Toluene	12.0	14.0	16.5	14.2
1,3,5-Trimethylbenzene	18.0	20.0	24.0	20.7
1,4-Dichlorobenzene	14.0	16.0	19.0	16.3

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	S6 (T=24) (ug/L)	S7 (T=25) (ug/L)	Avg	TUBE 62 (ng/L)	TUBE 69 (ng/L)	Avg (ng/L)
Dichloromethane	20.0	26.0	23.0	1126.4	1116.5	1121.5
Chloroform	13.0	14.0	13.5	464.5	338.7	401.6
1,1,1-Trichloroethane	2.4	4.1	3.3	264.4	254.5	259.5
Trichloroethylene	5.8	5.9	5.9	444.7	433.0	438.8
Toluene	7.1	6.4	6.8	415.8	407.8	411.8
Tetrachloroethylene	1.4	1.9	1.7	175.9	184.9	180.4
p-Xylene	5.6	5.2	5.4	455.3	450.0	452.7
4-Ethyl Toluene	3.4	3.1	3.3	368.1	372.0	370.0
1,3,5-Trimethylbenzene	5.4	4.9	5.2	394.5	386.4	390.5
1,4-Dichlorobenzene	6.2	4.8	5.5	370.1	364.8	367.5

Table A1.2- VOC Concentration Data; Dosed Tap Water Experiment II-A.2

INFLUENT CONCENTRATION

Compound	S11 (t=25) (ug/L)	S12 (t=26) (ug/L)	S16 (t=26) (ug/L)	Avg (ug/L)
Dichloromethane	43.0	31.5	32.0	35.5
Chloroform	27.0	40.0	39.0	35.3
1,1,1-Trichloroethane	7.6	12.5	10.0	10.0
Trichloroethylene	32.0	50.0	56.0	46.0
Toluene	42.0	39.5	40.0	40.5
Tetrachloroethylene	10.0	10.6	16.0	12.2
p-Xylene	48.0	44.0	46.0	46.0
4-Ethyl Toluene	44.0	40.0	42.0	42.0
1,3,5-Trimethylbenzene	61.0	55.0	59.0	58.3
1,4-Dichlorobenzene	36.0	33.5	38.0	35.8

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	S13 (t=25) (ug/L)	S14 (t=26) (ug/L)	Avg (ug/L)	TUBE 04 (ng/L)	TUBE 89 (ng/L)	Avg (ng/L)
Dichloromethane	20.0	19.0	19.5	1281.4	1320.6	1301.0
Chloroform	17.0	25.0	21.0	415.4	541.2	478.3
1,1,1-Trichloroethane	2.2	5.3	3.8	362.1	366.7	364.4
Trichloroethylene	12.0	17.0	14.5	536.3	550.2	543.2
Toluene	13.0	18.0	15.5	505.3	508.8	507.1
Tetrachloroethylene	4.4	4.1	4.3	235.5	238.4	237.0
p-Xylene	14.0	14.0	14.0	608.0	601.5	604.8
4-Ethyl Toluene	11.0	11.0	11.0	494.5	497.1	495.8
1,3,5-Trimethylbenzene	16.0	16.0	16.0	506.0	511.8	508.9
1,4-Dichlorobenzene	12.0	25.0	18.5	412.9	412.5	412.7

Table A1.3-VOC Concentration Data; Dosed Tap Water Experiment II-A.3

INFLUENT CONCENTRATION

Compound	(t=25)	S19 (t=25) (ug/L)	S24 (t=26) (ug/L)	S20 Avg (ug/L)
Dichloromethane	52.5	60.0	64.0	58.8
Chloroform	27.0	26.0	28.0	27.0
1,1,1-Trichloroethane	8.7	9.9	7.6	8.7
Trichloroethylene	32.5	38.0	34.0	34.8
Toluene	27.5	25.0	30.0	27.5
Tetrachloroethylene	4.3	6.2	5.0	5.2
p-Xylene	24.5	23.0	28.0	25.2
4-Ethyl Toluene	17.5	16.0	20.0	17.8
1,3,5-Trimethylbenzene	25.0	24.0	29.0	26.0
1,4-Dichlorobenzene	25.0	15.0	21.0	20.3

	EFFLUENT CONCENTRATION			**OFF-GAS CONCENTRATION**		
Compound	S21 (T=25) (ug/L)	S22 (T=26) (ug/L)	Avg (ug/L)	TUBE 19 (ng/L)	TUBE 95 (ng/L)	Avg (ng/L)
Dichloromethane	47.0	62.0	54.5	2001.8	1980.7	1991.2
Chloroform	3.4	5.0	4.2	704.9	689.0	697.0
1,1,1-Trichloroethane	0.6	1.7	1.2	772.1	764.6	768.4
Trichloroethylene	ND	2.1	2.1	962.0	960.6	961.3
Toluene	16.0	18.0	17.0	853.0	834.5	843.8
Tetrachloroethylene	1.0	2.6	1.8	397.3	381.7	389.5
p-Xylene	14.0	17.0	15.5	987.2	970.3	978.8
4-Ethyl Toluene	10.0	12.0	11.0	782.1	776.0	779.0
1,3,5-Trimethylbenzene	14.0	18.0	16.0	814.9	813.2	814.1
1,4-Dichlorobenzene	12.0	15.0	13.5	578.1	573.5	575.8

Table A1.4-VOC Concentration Data; Dosed Tap Water Experiment II-A.4

INFLUENT CONCENTRATION

Compound	S28 (t=25) (ug/L)	S29 (t=25) (ug/L)	S30 (t=26) (ug/L)	Avg (ug/L)
Dichloromethane	64.0	70.0	62.0	65.3
Chloroform	18.0	22.0	18.0	19.3
1,1,1-Trichloroethane	12.0	12.0	11.0	11.7
Trichloroethylene	41.0	38.0	37.0	38.7
Toluene	38.0	38.0	38.0	38.0
Tetrachloroethylene	7.4	7.0	6.6	7.0
p-Xylene	38.0	38.0	38.0	38.0
4-Ethyl Toluene	26.0	26.0	27.0	26.3
1,3,5-Trimethylbenzene	38.0	38.0	38.0	38.0
1,4-Dichlorobenzene	24.0	24.0	24.0	24.0

EFFLUENT CONCENTRATION

OFF-GAS CONCENTRATION

Compound	S31 (T=25) (ug/L)	S32 (T=26) (ug/L)	Avg (ug/L)	TUBE 33 (ng/L)	TUBE 51 (ng/L)	Avg (ng/L)
Dichloromethane	62.0	57.0	59.5	1608.5	1619.0	1613.7
Chloroform	12.0	13.0	12.5	543.0	543.0	543.0
1,1,1-Trichloroethane	2.0	1.2	1.6	472.8	474.8	473.8
Trichloroethylene	12.0	11.5	11.8	715.3	724.6	719.9
Toluene	14.0	14.5	14.3	642.3	643.3	642.8
Tetrachloroethylene	1.9	2.1	2.0	325.6	330.9	328.2
p-Xylene	12.0	13.0	12.5	760.3	760.5	760.4
4-Ethyl Toluene	8.4	9.1	8.7	621.8	626.1	624.0
1,3,5-Trimethylbenzene	13.0	14.0	13.5	815.7	800.4	808.1
1,4-Dichlorobenzene	14.0	16.5	15.3	676.7	686.7	681.7

Table A1.5-VOC Concentration Data; Dosed Tap Water Experiment II-A.5

INFLUENT CONCENTRATION

Compound	S33 (t=25) (ug/L)	S34 (t=25.5) (ug/L)	S36 (t=25.5) (ug/L)	S35 (t=26) (ug/L)	Avg (ug/L)
Dichloromethane	63.0	39.0	88.0	80.0	67.5
Chloroform	64.0	68.0	48.0	50.0	57.5
1,1,1-Trichloroethane	9.9	10.0	8.4	8.2	9.1
Trichloroethylene	36.0	33.0	30.0	32.0	32.8
Toluene	26.0	36.0	34.0	38.0	33.5
Tetrachloroethylene	6.6	6.0	4.8	6.0	5.9
p-Xylene	28.0	40.0	36.0	42.0	36.5
4-Ethyl Toluene	22.0	32.0	28.0	33.0	28.8
1,3,5-Trimethylbenzene	28.5	42.0	36.0	42.0	37.1
1,4-Dichlorobenzene	18.5	29.0	24.0	30.0	25.4

EFFLUENT CONCENTRATION						**OFF-GAS CONCENTRATION**
Compound	S37 (T=25) (ug/L)	S38 (T=25.5) (ug/L)	S39 Dupl (ug/L)	S40 Dupl (ug/L)	Avg (ug/L)	TUBE 29 (ng/L)
Dichloromethane	57.0	52.0	56.0	50.0	53.8	2047.6
Chloroform	35.0	21.0	19.0	19.0	23.5	892.4
1,1,1-Trichloroethane	4.0	1.8	0.8	2.8	2.4	450.0
Trichloroethylene	14.0	10.5	10.0	14.0	12.1	940.8
Toluene	10.0	11.0	10.0	11.0	10.5	668.6
Tetrachloroethylene	2.4	1.3	1.2	1.8	1.7	392.7
p-Xylene	10.0	11.0	10.0	11.0	10.5	933.9
4-Ethyl Toluene	7.2	7.3	7.6	8.2	7.6	615.1
1,3,5-Trimethylbenzene	10.0	10.0	11.0	12.0	10.8	654.9
1,4-Dichlorobenzene	10.0	10.5	10.0	12.0	10.6	568.2

Table A1.6-VOC Concentration Data; Dosed Tap Water Experiment II-A.6

INFLUENT CONCENTRATION

Compound	S41 (t=24) (ug/L)	S42 (t=24) (ug/L)	S43 (t=25) (ug/L)	S44 (t=26) (ug/L)	Avg (ug/L)
Dichloromethane	75.5	70.0	60.0	49.0	63.6
Chloroform	17.0	30.0	28.0	29.0	26.0
1,1,1-Trichloroethane	5.9	15.0	12.0	9.9	10.7
Trichloroethylene	28.5	20.0	14.0	26.0	22.1
Toluene	33.0	30.0	32.0	28.0	30.8
Tetrachloroethylene	3.7	4.7	3.4	4.6	4.1
p-Xylene	33.5	30.0	33.0	28.0	31.1
4-Ethyl Toluene	23.0	20.0	23.0	19.0	21.3
1,3,5-Trimethylbenzene	34.0	30.0	34.0	28.0	31.5
1,4-Dichlorobenzene	24.0	19.0	23.0	16.0	20.5

EFFLUENT CONCENTRATION

Compound	S45 (T=24) (ug/L)	S46 (T=25) (ug/L)	S47 (T=25) (ug/L)	S48 (T=26) (ug/L)	Avg (ug/L)
Dichloromethane	2.2	3.4	1.4	1.7	2.2
Chloroform	26.0	48.0	23.0	16.0	28.3
1,1,1-Trichloroethane	4.6	5.6	1.6	1.0	3.2
Trichloroethylene	14.0	26.0	6.6	8.7	13.8
Toluene	14.0	12.0	12.0	14.5	13.1
Tetrachloroethylene	2.2	3.4	1.4	1.7	2.2
p-Xylene	13.0	12.0	12.0	14.0	12.8
4-Ethyl Toluene	8.4	7.2	6.8	9.2	7.9
1,3,5-Trimethylbenzene	13.0	12.0	10.0	14.5	12.4
1,4-Dichlorobenzene	12.0	10.0	10.0	13.5	11.4

OFF-GAS CONCENTRATION

Compound	TUBE 12 (ng/L)	TUBE 65 (ng/L)	Avg (ng/L)
Dichloromethane	2162.8	2140.2	2151.5
Chloroform	770.9	761.7	766.3
1,1,1-Trichloroethane	481.1	475.6	478.3
Trichloroethylene	1034.0	1001.2	1017.6
Toluene	740.0	716.8	728.4
Tetrachloroethylene	454.3	456.9	455.6
p-Xylene	995.1	953.0	974.0
4-Ethyl Toluene	667.4	640.3	653.8
1,3,5-Trimethylbenzene	717.7	692.4	705.1
1,4-Dichlorobenzene	619.8	608.0	613.9

Table A1.7-VOC Concentration Data; Dosed Tap Water Experiment
II-A.7

INFLUENT CONCENTRATION

Compound	B50 (t=25) (ug/L)	B51 (T=26) (ug/L)	Avg (ug/L)
Dichloromethane	66.5	54.6	60.6
Chloroform	58.0	57.2	57.6
1,1,1-Trichloroethane	15.3	17.6	16.5
Trichloroethylene	34.9	33.0	34.0
Toluene	33.3	32.1	32.7
Tetrachloroethylene	11.8	12.6	12.2
p-Xylene	25.2	25.9	25.6
4-Ethyl Toluene	15.3	15.5	15.4
1,3,5-Trimethylbenzene	20.5	21.6	21.1
1,4-Dichlorobenzene	12.1	11.6	11.9

EFFLUENT CONCENTRATION				**OFF-GAS CONCENTRATION**
Compound	B52 (T=25) (ug/L)	B53 (T=26) (ug/L)	Avg (ug/L)	TUBE 2 (ng/L)
Dichloromethane	30.1	16.9	23.5	1462.2
Chloroform	7.0	7.0	7.0	629.7
1,1,1-Trichloroethane	0.8	0.7	0.8	146.7
Trichloroethylene	2.8	2.1	2.5	724.2
Toluene	2.2	0.6	1.4	612.5
Tetrachloroethylene	0.7	0.5	0.6	334.8
p-Xylene	0.9	0.6	0.8	646.5
4-Ethyl Toluene	0.6	0.4	0.5	420.7
1,3,5-Trimethylbenzene	0.2	0.1	0.2	504.9
1,4-Dichlorobenzene	3.4	3.4	3.4	392.7

Table A1.8-VOC Concentration Data; Dosed Tap Water Experiment II-A.8

INFLUENT CONCENTRATION

Compound	B54 (t=25) (ug/L)	B55 (T=26) (ug/L)	Avg (ug/L)
Dichloromethane	60.4	77.6	69.0
Chloroform	35.7	39.0	37.4
1,1,1-Trichloroethane	8.5	10.6	9.6
Trichloroethylene	23.0	33.9	28.5
Toluene	27.0	32.1	29.6
Tetrachloroethylene	5.4	7.6	6.5
p-Xylene	24.9	26.2	25.6
4-Ethyl Toluene	15.4	16.5	16.0
1,3,5-Trimethylbenzene	20.4	11.2	15.8
1,4-Dichlorobenzene	11.2	11.4	11.3

EFFLUENT CONCENTRATION				OFF-GAS CONCENTRATION
Compound	B56 (T=25) (ug/L)	B57 (T=26) (ug/L)	Avg (ug/L)	TUBE 41 (ng/L)
Dichloromethane	46.2	32.6	39.4	2818.5
Chloroform	16.5	13.9	15.2	1289.1
1,1,1-Trichloroethane	1.8	1.5	1.7	620.2
Trichloroethylene	8.9	6.4	7.6	1582.5
Toluene	8.7	6.8	7.7	1213.4
Tetrachloroethylene	1.2	0.9	1.1	747.8
p-Xylene	6.5	6.2	6.4	1256.0
4-Ethyl Toluene	3.6	3.3	3.4	921.1
1,3,5-Trimethylbenzene	4.5	4.3	4.4	948.3
1,4-Dichlorobenzene	6.2	6.2	6.2	654.7

Appendix A2-Experimental Conditions and VOC Concentration Data; Dosed Wastewater Experiments; Burlington Skyway Wastewater, 5 day SRT

EXPERIMENTAL CONDITIONS:

EXPERIMENT NUMBER	DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
II-B.1.1	COARSE	10.6	4.85	29.0	19.0	745
II-B.1.2	COARSE	21.3	5.00	34.0	18.0	555
II-B.1.3	COARSE	7.1	4.75	26.0	18.0	425
II-B.1.4	COARSE	23.1	5.30	35.5	18.0	490
II-B.1.5	FINE	17.8	5.10	33.0	20.0	450
II-B.1.6	FINE	5.3	4.80	25.0	20.0	390
II-B.1.7	FINE	17.8	5.40	41.0	25.5	920
II-B.1.8	COARSE	7.1	4.95	32.0	25.0	1200

Table A2.1-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.1, Burlington Skyway Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION S54 (t=25) (ug/L)	S55 (t=25) (ug/L)	S56 (t=26) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION S60 (t=25.5) (ug/L)
Dichloromethane	72.0	70.5	240.0	127.5	ND
Chloroform	130.0	31.0	90.0	83.7	36.5
1,1,1-Trichloroethane	500.0	65.5	300.0	288.5	5.4
Trichloroethylene	96.0	117.0	160.0	124.3	2.2
Toluene	24.0	36.0	10.0	23.3	26.5
Tetrachloroethylene	93.0	99.0	100.0	97.3	9.4
p-Xylene	27.0	28.5	11.[illegible]	22.2	ND
4-Ethyl Toluene	20.0	19.5	9.6	16.4	ND
1,3,5-Trimethylbenzene	32.0	22.0	17.0	23.7	ND
1,4-Dichlorobenzene	11.0	11.0	5.5	9.2	14.0

Compound	EFFLUENT CONCENTRATION S57 (t=24) (ug/L)	S58 (t=24) (ug/L)	S59 (t=25) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 10 (ng/L)	TUBE 11 (ng/L)	Avg (ng/L)
Dichloromethane	24.0	43.0	28.0	31.7	1070.3	999.6	1035.0
Chloroform	4.9	39.0	48.0	30.6	481.6	481.9	481.8
1,1,1-Trichloroethane	1.2	0.8	1.4	1.1	321.1	308.9	315.0
Trichloroethylene	2.6	1.8	1.8	2.1	661.9	659.7	660.8
Toluene	ND	0.3	0.3	0.3	47.8	44.9	46.4
Tetrachloroethylene	1.6	4.0	6.4	4.0	1049.0	1031.7	1040.3
p-Xylene	ND	ND	ND	ND	25.4	26.4	25.9
4-Ethyl Toluene	ND	ND	ND	ND	14.2	14.1	14.2
1,3,5-Trimethylbenzene	ND	ND	ND	ND	18.7	20.1	19.4
1,4-Dichlorobenzene	3.1	4.2	2.8	3.4	373.5	373.8	373.6

Table A2.2-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.2; Burlington Skyway Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION S61 (t=25) (ug/L)	S62 (t=25) (ug/L)	S63 (t=26) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION S67 (t=25.5) (ug/L)
Dichloromethane	30.0	31.0	72.0	51.0	39.0
Chloroform	77.0	48.5	17.0	47.5	0.6
1,1,1-Trichloroethane	38.0	26.0	20.0	28.0	0.2
Trichloroethylene	46.0	37.0	60.0	47.7	0.9
Toluene	68.0	55.5	35.0	52.8	1.0
Tetrachloroethylene	4.8	10.3	36.0	17.0	2.0
p-Xylene	36.0	36.0	37.0	36.3	1.4
4-Ethyl Toluene	30.0	31.0	30.0	30.3	ND
1,3,5-Trimethylbenzene	36.0	37.0	39.0	37.3	ND
1,4-Dichlorobenzene	35.0	43.5	42.0	40.2	50.5

Compound	EFFLUENT CONCENTRATION S64 (t=24) (ug/L)	S65 (t=25) (ug/L)	S66 (t=25) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 95 (ng/L)	TUBE 75 (ng/L)	Avg (ng/L)
Dichloromethane	14.0	16.0	11.0	13.7	638.5	496.8	567.7
Chloroform	15.5	2.6	2.2	6.8	262.9	222.4	242.7
1,1,1-Trichloroethane	16.0	1.2	1.1	6.1	94.0	90.7	92.4
Trichloroethylene	0.8	1.6	1.1	1.2	307.4	279.5	293.4
Toluene	1.3	0.3	0.3	0.6	1875.8	1560.3	1718.1
Tetrachloroethylene	4.3	0.8	0.4	1.8	221.0	218.9	219.9
p-Xylene	ND	ND	ND	ND	36.1	29.8	32.9
4-Ethyl Toluene	ND	ND	ND	ND	6.2	16.2	11.2
1,3,5-Trimethylbenzene	ND	ND	ND	ND	24.3	23.0	23.7
1,4-Dichlorobenzene	3.5	4.8	5.2	4.5	336.4	342.6	339.5

Table A2.3-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.3; Burlington Skyway Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION S68 (t=24) (ug/L)	S69 (t=24) (ug/L)	S70 (t=25) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION S74 (t=24.5) (ug/L)
Dichloromethane	115.0	--	100.0	107.5	69.5
Chloroform	25.5	5.0	12.0	14.2	1.1
1,1,1-Trichloroethane	22.0	16.0	32.0	23.3	0.3
Trichloroethylene	51.0	11.0	27.0	29.7	2.9
Toluene	36.5	23.0	40.0	33.2	ND
Tetrachloroethylene	15.0	4.0	8.4	9.1	5.7
p-Xylene	29.5	16.0	39.0	28.2	ND
4-Ethyl Toluene	32.5	22.0	53.0	35.8	ND
1,3,5-Trimethylbenzene	28.0	17.0	34.0	26.3	ND
1,4-Dichlorobenzene	14.0	9.5	14.0	12.5	42.0

Compound	EFFLUENT CONCENTRATION S71 (t=24) (ug/L)	S72 (t=25) (ug/L)	S73 (t=25) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 95 (ng/L)
Dichloromethane	37.0	38.0	52.0	42.3	2764.4
Chloroform	8.6	12.0	12.0	10.9	635.6
1,1,1-Trichloroethane	1.4	1.4	1.8	1.5	305.7
Trichloroethylene	2.8	3.0	5.2	3.7	614.8
Toluene	0.6	0.4	0.4	0.5	1716.1
Tetrachloroethylene	2.1	1.8	2.4	2.1	518.0
p-Xylene	ND	ND	ND	ND	42.8
4-Ethyl Toluene	ND	ND	ND	ND	15.7
1,3,5-Trimethylbenzene	ND	ND	ND	ND	20.6
1,4-Dichlorobenzene	11.0	8.0	7.0	8.7	496.5

Table A2.4-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.4, Burlington Skyway Wastewater, 5 day SRT

	INFLUENT CONCENTRATION				RECYCLE SLUDGE CONCENTRATION
Compound	S75 (t=24) (ug/L)	S76 (t=24) (ug/L)	S77 (t=25) (ug/L)	Avg (ug/L)	S81 (t=1.5) (ug/L)
Dichloromethane	25.0	790.0	100.0	62.5	44.0
Chloroform	36.0	46.0	36.0	39.3	0.1
1,1,1-Trichloroethane	5.0	20.0	17.0	14.0	0.1
Trichloroethylene	8.6	29.0	38.0	25.2	1.4
Toluene	28.0	1.7	16.0	15.2	2.0
Tetrachloroethylene	2.4	8.2	14.0	8.2	3.4
p-Xylene	22.0	2.7	20.0	14.9	ND
4-Ethyl Toluene	16.0	16.0	14.0	15.3	ND
1,3,5-Trimethylbenzene	19.0	19.0	22.0	20.0	ND
1,4-Dichlorobenzene	6.4	6.4	8.9	7.2	7.6

	EFFLUENT CONCENTRATION				OFF-GAS CONCENTRATION
Compound	S78 (t=24)	S79 (t=25) (ug/L)	S80 (t=25) (ug/L)	Avg (ug/L)	TUBE 83 (ug/L)
Dichloromethane	6.4	8.6	15.0	10.0	1194.5
Chloroform	6.7	4.2	4.8	5.2	633.3
1,1,1-Trichloroethane	0.8	1.2	1.4	1.1	108.0
Trichloroethylene	1.8	2.0	2.1	2.0	698.1
Toluene	0.2	0.2	0.2	0.2	2765.4
Tetrachloroethylene	0.6	0.5	0.5	0.5	335.8
p-Xylene	ND	ND	ND	ND	86.1
4-Ethyl Toluene	ND	ND	ND	ND	11.8
1,3,5-Trimethylbenzene	ND	ND	ND	ND	38.9
1,4-Dichlorobenzene	1.2	1.0	0.7	1.0	364.5

Table A2.5-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.5, Burlington Skyway Wastewater, 5 day SRT

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	S02 (t=24) (ug/L)	S03 (t=25) (ug/L)	Avg (ug/L)	S03 (t=24.5) (ug/L)
Dichloromethane	270.0	280.0	275.0	31.5
Chloroform	24.0	20.0	22.0	5.8
1,1,1-Trichloroethane	20.0	14.0	17.0	2.6
Trichloroethylene	14.0	20.0	17.0	4.8
Toluene	55.0	40.0	47.5	0.9
Tetrachloroethylene	38.0	10.0	24.0	6.1
p-Xylene	87.0	84.0	85.5	ND
4-Ethyl Toluene	42.0	38.0	40.0	ND
1,3,5-Trimethylbenzene	31.0	29.0	30.0	ND
1,4-Dichlorobenzene	13.0	12.0	12.5	11.6

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION
Compound	S04 (T=24) (ug/L)	S05 (T=25) (ug/L)	Avg (ug/L)	TUBE 76 (ng/L)
Dichloromethane	41.0	42.0	41.5	760.5
Chloroform	11.6	5.6	8.6	215.1
1,1,1-Trichloroethane	6.7	2.8	4.7	241.1
Trichloroethylene	5.8	3.4	4.6	382.6
Toluene	0.2	0.2	0.2	619.0
Tetrachloroethylene	7.9	3.7	5.8	751.4
p-Xylene	ND	ND	ND	60.5
4-Ethyl Toluene	ND	ND	ND	12.9
1,3,5-Trimethylbenzene	ND	ND	ND	21.9
1,4-Dichlorobenzene	1.6	2.5	2.1	179.2

Table A2.6-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.6; Burlington Skyway Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
	S87 (t=25) (ug/L)	S88 (t=26) (ug/L)	Avg (ug/L)	S91 (t=25.5) (ug/L)
Dichloromethane	120.0	78.0	99.0	205.0
Chloroform	36.0	21.0	28.5	1.8
1,1,1-Trichloroethane	14.0	18.0	16.0	0.6
Trichloroethylene	34.0	13.0	23.5	4.9
Toluene	30.0	24.0	27.0	5.8
Tetrachloroethylene	12.0	8.2	10.1	1.8
p-Xylene	21.0	16.0	18.5	ND
4-Ethyl Toluene	14.0	10.0	12.0	ND
1,3,5-Trimethylbenzene	17.0	12.0	14.5	ND
1,4-Dichlorobenzene	16.0	16.0	16.0	17.5

Compound	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION
	S89 (t=25 (ug/L)	S90 (t=26) (ug/L)	Avg (ug/L)	TUBE 86 (ng/L)
Dichloromethane	36.0	23.0	29.5	1709.7
Chloroform	6.6	8.2	7.4	832.1
1,1,1-Trichloroethane	4.6	3.1	3.9	1149.5
Trichloroethylene	3.4	4.5	4.0	1432.6
Toluene	0.5	1.6	1.0	535.6
Tetrachloroethylene	2.2	1.5	1.9	1142.9
p-Xylene	ND	ND	ND	50.9
4-Ethyl Toluene	ND	ND	ND	20.8
1,3,5-Trimethylbenzene	ND	ND	ND	27.7
1,4-Dichlorobenzene	4.6	4.7	4.7	601.0

Table A2.7-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.7; Burlington Skyway Wastewater, 5 day SRT

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	S97 (t=25) (ug/L)	S98 (t=26) (ug/L)	Avg (ug/L)	S91 (t=25.5) (ug/L)
Dichloromethane	160.0	160.0	160.0	ND
Chloroform	36.0	42.0	39.0	1.6
1,1,1-Trichloroethane	20.0	13.0	16.5	0.5
Trichloroethylene	36.0	42.0	39.0	1.6
Toluene	41.0	31.0	36.0	ND
Tetrachloroethylene	34.0	37.0	35.5	5.4
p-Xylene	31.0	26.0	28.0	0.9
4-Ethyl Toluene	24.0	18.0	21.0	ND
1,3,5-Trimethylbenzene	32.0	22.0	27.0	ND
1,4-Dichlorobenzene	13.0	28.0	20.5	10

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION
Compound	S99 (t=25) (ug/L)	S100 (t=26) (ug/L)	Avg (ug/L)	TUBE 31 (ng/L)
Dichloromethane	0.0	33.0	16.5	1339.1
Chloroform	3.6	3.4	3.5	400.2
1,1,1-Trichloroethane	1.2	0.8	1.0	141.8
Trichloroethylene	2.4	1.3	1.8	554.8
Toluene	0.8	0.6	0.7	131.8
Tetrachloroethylene	0.6	0.6	0.6	705.6
p-Xylene	ND	ND	ND	77.8
4-Ethyl Toluene	ND	ND	ND	6.1
1,3,5-Trimethylbenzene	ND	ND	ND	35.9
1,4-Dichlorobenzene	2.2	1.6	1.9	343.0

Table A2.8-VOC Concentration Data; Dosed Wastewater Experiment II-B.1.8; Burlington Skyway Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION C40 (t=25) (ug/L)	C41 (t=26) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION C45 (t=25.5) (ug/L)
Dichloromethane	11.3	10.7	11.0	5.1
Chloroform	31.8	31.3	31.6	5.4
1,1,1-Trichloroethane	13.1	14.5	13.8	2.4
Trichloroethylene	31.7	31.7	31.7	3.3
Toluene	4.8	4.8	4.8	2.5
Tetrachloroethylene	42.2	36.9	39.6	3.1
p-Xylene	21.6	20.4	21.0	ND
4-Ethyl Toluene	44.7	40.2	42,5	ND
1,3,5-Trimethylbenzene	10.7	10.0	10.4	ND
1,4-Dichlorobenzene	13.0	28.0	20.5	2.7

Compound	EFFLUENT CONCENTRATION C42 (t=25) (ug/L)	C43 (t=26) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 74 (ng/L)
Dichloromethane	3.3	6.3	4.8	1707.2
Chloroform	9.5	7.4	8.5	614.3
1,1,1-Trichloroethane	2.2	3.4	2.8	264.3
Trichloroethylene	5.1	3.9	4.5	693.3
Toluene	1.2	2.4	1.8	204.9
Tetrachloroethylene	4.2	4.1	4.2	954,2
p-Xylene	ND	ND	ND	91.3
4-Ethyl Toluene	ND	ND	ND	4.4
1,3,5-Trimethylbenzene	ND	ND	ND	55.4
1,4-Dichlorobenzene	4.1	3.1	3.6	521.2

Appendix A3-Experimental Conditions and VOC Concentration Data; Non-Dosed Wastewater Experiments, 5 day SRT

EXPERIMENTAL CONDITIONS:

EXPERIMENT NUMBER	DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
II-B.1.9	COARSE	7.1	4.8	29.0	19.0	1420
II-B.1.10	COARSE	21.3	4.9	40.0	20.5	1330

Table A3.1-VOC Concentration Data; Non-Dosed Wastewater ExperimentII-B.1.9; Burlington Skyway Wastewater, 5 day SRT

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	B01 (t=25) (ug/L)	B03 (t=26) (ug/L)	Avg (ug/L)	B07 (t=25.5) (ug/L)
Dichloromethane	154.0	184.0	169.0	12.7
Chloroform	3.1	3.2	3.2	ND
1,1,1-Trichloroethane	4.5	5.6	4.9	0.2
Trichloroethylene	1.8	2.4	2.1	ND
Toluene	6.0	14.4	10.2	0.8
Tetrachloroethylene	9.0	11.4	10.2	0.9
p-Xylene	5.8	4.6	5.2	ND
4-Ethyl Toluene	4.3	4.3	4.3	ND
1,3,5-Trimethylbenzene	2.6	2.7	2.6	ND
1,4-Dichlorobenzene	3.1	3.1	3.1	0.7

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION
Compound	B04 (t=25) (ug/L)	B06 (t=26) (ug/L)	Avg (ug/L)	TUBE 74 (ng/L)
Dichloromethane	6.8	13.2	10.0	1642.2
Chloroform	0.7	0.8	0.8	76.5
1,1,1-Trichloroethane	0.8	0.5	0.7	180.9
Trichloroethylene	0.2	0.2	0.2	57.5
Toluene	0.1	ND	0.1	685.7
Tetrachloroethylene	0.6	1.1	0.9	495.7
p-Xylene	ND	ND	ND	32.0
4-Ethyl Toluene	ND	ND	ND	9.4
1,3,5-Trimethylbenzene	ND	ND	ND	7.6
1,4-Dichlorobenzene	0.6	1.0	0.8	102.7

Table A3.2-VOC Concentration Data; Non-Dosed Wastewater Experiment II-B.1.10; Burlington Skyway Wastewater, 5 day SRT

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	B08 (t=25) (ug/L)	B09 (t=26) (ug/L)	Avg (ug/L)	B12 (t=25.5) (ug/L)
Dichloromethane	78.3	111.0	94.7	3.9
Chloroform	4.3	9.1	6.7	0.6
1,1,1-Trichloroethane	1.9	1.6	1.8	0.1
Trichloroethylene	1.5	1.5	1.5	0.1
Toluene	5.7	5.1	5.4	0.1
Tetrachloroethylene	4.9	9.0	7.0	0.2
p-Xylene	2.3	2.4	2.4	ND
4-Ethyl Toluene	5.6	6.8	6.2	ND
1,3,5-Trimethylbenzene	2.9	3.0	3.0	ND
1,4-Dichlorobenzene	3.5	3.2	3.4	0.3

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION
Compound	B10 (t=25) (ug/L)	B11 (t=26) (ug/L)	Avg (ug/L)	TUBE 100 (ng/L)
Dichloromethane	1.5	4.6	2.9	600.6
Chloroform	0.4	0.5	0.4	47.9
1,1,1-Trichloroethane	0.1	0.1	0.1	29.7
Trichloroethylene	0.1	0.1	0.1	25.4
Toluene	0.2	0.2	0.2	812.5
Tetrachloroethylene	0.2	0.3	0.2	150.8
p-Xylene	ND	ND	ND	19.6
4-Ethyl Toluene	ND	ND	ND	6.3
1,3,5-Trimethylbenzene	ND	ND	ND	6.4
1,4-Dichlorobenzene	0.3	0.4	0.3	58.1

Appendix A4-Experimental Conditions and VOC Concentration Data; Dosed Wastewater Experiments; Burlington Skyway Wastewater, 10 day SRT

EXPERIMENTAL CONDITIONS:

EXPERIMENT NUMBER	DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
II-B.2.1	FINE	17.8	5.7	27.0	17.5	800
II-B.2.2	FINE	17.6	5.5	27.5	16.0	790
II-B.2.3	COARSE	21.3	5.6	18.0	15.5	990
II-B.2.4	COARSE	7.0	5.6	26.0	16.5	700
II-B.2.5	FINE	5.9	5.6	30.0	17.0	795

Table A4.1 - VOC Concentration Data; Dosed Wastewater Experiment II-B.2.1, Burlington Skyway Wastewater, 10 day SRT

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	001H (t=24) (ug/L)	002H (t=25) (ug/L)	Avg (ug/L)	005H (t=24.5) (ug/L)
Chloroform	93.0	32.0	62.5	6.4
1,1,1-Trichloroethane	19.5	17.0	18.3	2.7
Trichloroethylene	43.5	20.0	31.8	1.3
Toluene	18.0	10.0	14.0	0.9
Tetrachloroethylene	17.0	8.6	12.8	0.5
p-Xylene	15.5	8.4	12.0	ND
4-Ethyl Toluene	14.0	9.3	11.7	ND
1,3,5-Trimethylbenzene	16.0	10.0	13.0	ND
1,4-Dichlorobenzene	5.7	3.5	4.6	ND

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	003H (T=24) (ug/L)	004H (T=25) (ug/L)	Avg (ug/L)	TUBE 2 (ng/L)	TUBE 52 (ng/L)	Avg (ng/L)
Chloroform	6.4	6.6	6.5	536.1	570.0	553.1
1,1,1-Trichloroethane	1.8	1.2	1.5	266.3	306.7	286.5
Trichloroethylene	2.1	1.8	2.0	543.0	632.7	587.8
Toluene	0.7	ND	0.3	40.3	63.3	51.8
Tetrachloroethylene	0.7	0.6	0.6	249.1	233.3	241.2
p-Xylene	ND	ND	ND	17.0	24.7	20.8
4-Ethyl Toluene	ND	ND	ND	11.9	13.3	12.6
1,3,5-Trimethylbenzene	ND	ND	ND	14.0	15.3	14.7
1,4-Dichlorobenzene	2.7	ND	1.4	281.9	290.0	285.9

Table A4.2 - VOC Concentration Data; Dosed Wastewater Experiment II-B.2.2, Burlington Skyway Wastewater, 10 day SRT

Compound	INFLUENT CONCENTRATION 006H (t=24) (ug/L)	 007H (t=25) (ug/L)	 Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION 010H (t=24.5) (ug/L)
Dichloromethane	105.0	88.0	96.5	ND
Chloroform	16.0	16.0	16.0	2.8
1,1,1-Trichloroethane	9.4	8.8	9.1	0.7
Trichloroethylene	2.4	1.6	2.0	0.1
Toluene	30.0	30.0	30.0	0.3
Tetrachloroethylene	8.3	7.8	8.1	0.6
p-Xylene	30.0	28.0	29.0	ND
4-Ethyl Toluene	36.0	20.0	28.0	ND
1,3,5-Trimethylbenzene	24.0	28.0	26.0	ND
1,4-Dichlorobenzene	10.0	5.6	7.8	1.0

Compound	EFFLUENT CONCENTRATION 008H (T=24) (ug/L)	 009H (T=25) (ug/L)	 Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 18 (ng/L)	 TUBE 44 (ng/L)	 Avg (ng/L)
Dichloromethane	ND	ND	ND	2029.1	1894.2	1961.7
Chloroform	2.2	3.0	2.6	139.9	136.8	138.3
1,1,1-Trichloroethane	0.8	0.7	0.8	151.3	153.3	152.3
Trichloroethylene	0.1	0.1	0.1	31.1	30.3	30.7
Toluene	0.2	2.7	1.5	57.1	47.2	52.2
Tetrachloroethylene	0.6	0.7	0.6	202.0	200.6	201.3
p-Xylene	ND	ND	ND	27.5	27.2	27.3
4-Ethyl Toluene	ND	ND	ND	17.1	12.9	15.0
1,3,5-Trimethylbenzene	ND	ND	ND	12.3	15.6	13.9
1,4-Dichlorobenzene	1.0	1.3	1.1	154.9	154.8	154.9

Table A4.3 - VOC Concentration Data; Dosed Wastewater Experiment II-B.2.3, Burlington Skyway Wastewater, 10 day SRT

Compound	INFLUENT CONCENTRATION 011H (t=24) (ug/L)	012H (t=25) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION 015H (t=24.5) (ug/L)
Dichloromethane	128.0	134.0	131.0	ND
Chloroform	36.0	36.0	36.0	4.3
1,1,1-Trichloroethane	16.0	18.0	17.0	1.5
Trichloroethylene	26.0	21.0	23.5	4.4
Toluene	27.0	25.0	26.0	1.1
Tetrachloroethylene	16.0	12.0	14.0	6.3
p-Xylene	32.0	26.0	29.0	1.0
4-Ethyl Toluene	26.0	22.0	24.0	ND
1,3,5-Trimethylbenzene	34.0	27.0	30.5	ND
1,4-Dichlorobenzene	17.0	18.0	17.5	12.0

Compound	EFFLUENT CONCENTRATION 013H (T=24) (ug/L)	014H (T=25) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 76 (ng/L)	TUBE 86 (ng/L)	Avg (ng/L)
Dichloromethane	ND	36	18.0	12.6	2006.1	1009.3
Chloroform	6.6	5.2	5.9	3.5	380.5	192.0
1,1,1-Trichloroethane	2.8	3.2	3.0	6.7	166.5	86.6
Trichloroethylene	1.2	1.5	1.4	15.4	503.0	259.2
Toluene	ND	ND	ND	27.2	70.5	48.9
Tetrachloroethylene	0.6	1.6	1.1	138.9	420.5	279.7
p-Xylene	ND	ND	ND	14.1	28.4	21.2
4-Ethyl Toluene	ND	ND	ND	11.0	17.4	14.2
1,3,5-Trimethylbenzene	ND	ND	ND	13.7	21.5	17.6
1,4-Dichlorobenzene	2.4	2.6	2.5	251.4	344.2	297.8

Table A4.4 - VOC Concentration; Dosed Wastewater Experiment II-B.2.4, Burlington Skyway Wastewater, 10 day SRT

Compound	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
	016H (t=24) (ug/L)	017H (t=25) (ug/L)	Avg (ug/L)	020H (t=24.5) (ug/L)
Dichloromethane	242.0	174.0	208.0	20.0
Chloroform	32.0	34.0	33.0	6.6
1,1,1-Trichloroethane	14.5	16.0	15.3	2.1
Trichloroethylene	25.5	28.0	26.8	5.5
Toluene	49.5	56.0	52.8	ND
Tetrachloroethylene	10.2	11.0	10.6	5.8
p-Xylene	41.0	43.0	42.0	ND
4-Ethyl Toluene	30.0	29.0	29.5	ND
1,3,5-Trimethylbenzene	25.0	28.0	26.5	ND
1,4-Dichlorobenzene	24.0	32.0	28.0	2.2

Compound	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
	018H (T=24) (ug/L)	019H (T=25) (ug/L)	Avg (ug/L)	TUBE 98 (ng/L)	TUBE 23 (ng/L)	Avg (ng/L)
Dichloromethane	32.0	23.0	27.5	3247.1	4078.3	3662.7
Chloroform	6.0	6.0	6.0	0.0	828.7	414.3
1,1,1-Trichloroethane	1.6	1.2	1.4	434.1	461.5	447.8
Trichloroethylene	3.7	3.2	3.5	1097.0	1212.7	1154.9
Toluene	ND	ND	ND	149.3	199.6	174.4
Tetrachloroethylene	1.3	1.0	1.1	759.4	752.4	755.9
p-Xylene	ND	ND	ND	9.6	75.5	42.5
4-Ethyl Toluene	ND	ND	ND	21.9	11.2	16.5
1,3,5-Trimethylbenzene	ND	ND	ND	18.7	21.4	20.1
1,4-Dichlorobenzene	4.4	3.6	4.0	563.4	555.2	559.3

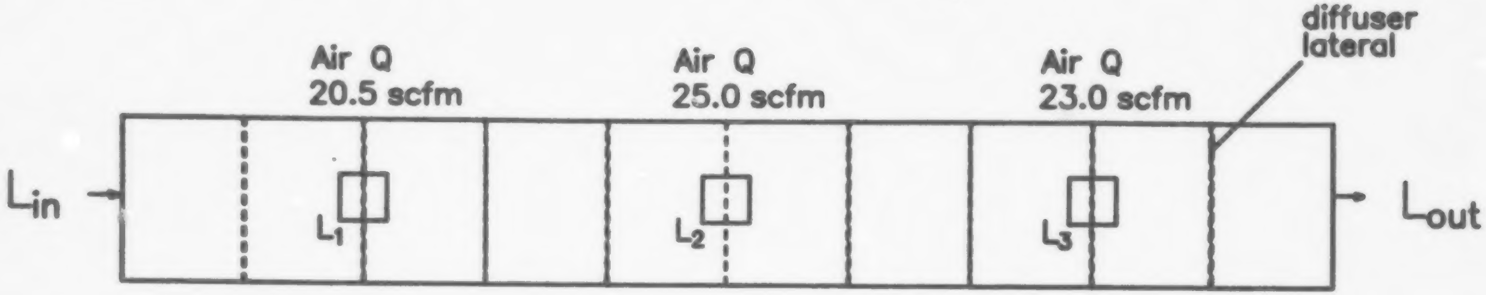
Table A4.5 - VOC Concentration Data; Dosed Wastewater Experiment II-B.2.5, Burlington Skyway Wastewater, 10 day SRT

Compound	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
	021H (t=24) (ug/L)	022H (t=25) (ug/L)	Avg (ug/L)	025H (t=24.5) (ug/L)
Dichloromethane	260.0	140.0	200.0	17.0
Chloroform	34.0	37.0	35.5	3.7
1,1,1-Trichloroethane	24.0	16.0	20.0	0.9
Trichloroethylene	50.0	38.0	44.0	5.0
Toluene	50.0	46.0	48.0	ND
Tetrachloroethylene	20.0	12.0	16.0	1.8
p-Xylene	52.0	45.0	48.5	ND
4-Ethyl Toluene	42.0	37.0	39.5	ND
1,3,5-Trimethylbenzene	27.0	31.0	29.0	ND
1,4-Dichlorobenzene	24.0	43.0	33.5	ND

Compound	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
	023H (T=24) (ug/L)	024H (T=25) (ug/L)	Avg (ug/L)	TUBE 18 (ng/L)	TUBE 17 (ng/L)	Avg (ng/L)
Dichloromethane	54.0	40.0	47.0	2088.1	2069.5	2078.8
Chloroform	5.6	6.1	5.8	740.3	731.7	736.0
1,1,1-Trichloroethane	1.0	0.9	0.9	429.7	418.0	423.9
Trichloroethylene	3.0	3.9	3.4	545.2	528.0	536.6
Toluene	ND	ND	ND	116.6	112.0	114.3
Tetrachloroethylene	0.7	0.7	0.7	702.4	682.7	692.5
p-Xylene	ND	ND	ND	43.4	43.9	43.6
4-Ethyl Toluene	ND	ND	ND	32.2	31.3	31.8
1,3,5-Trimethylbenzene	ND	ND	ND	38.9	37.8	38.3
1,4-Dichlorobenzene	5.0	5.9	5.5	572.7	559.8	566.2

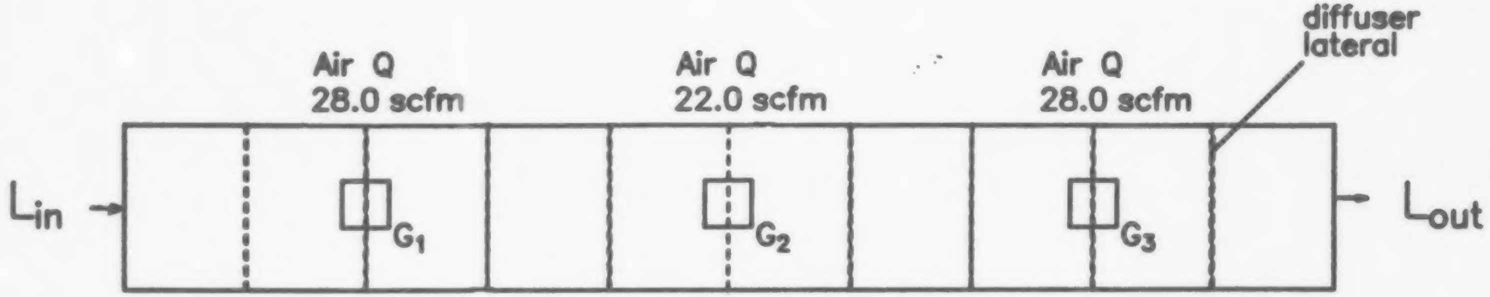
APPENDIX A5-VOC CONCENTRATION DATA; BURLINGTON SKYWAY FULL SCALE AERATION BASIN SAMPLING

EXPERIMENT II-B.3.1:


Air Q
20.5 scfm
Air Q
25.0 scfm
Air Q
23.0 scfm
diffuser
lateral
L_{in}
L_1
L_2
L_3
L_{out}

Compound	L_{in}	L_1		L_2		L_3		L_{out}
	T=0.5 h (ug/L)	T= 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0.5 h (ug/L)
Dichloromethane	14.0	8.0	12.1	5.5	5.8	3.8	4.8	2.8
Chloroform	5.4	0.7	1.2	2.0	1.9	0.8	0.3	1.8
1,1,1-Trichloroethane	1.3	0.6	0.7	ND	ND	ND	ND	ND
Trichloroethylene	4.6	2.2	3.6	0.8	0.9	0.6	1.0	ND
Toluene	12.0	0.8	ND	ND	ND	ND	0.4	ND
Tetrachloroethylene	ND	ND	17.2	5.9	6.2	2.9	3.9	ND
m/p Xylene	ND	ND	0.8	ND	ND	ND	ND	ND
4-Ethyl Toluene	165.0	5.4	23.1	ND	ND	ND	ND	ND
1,3,5-Trimethylbenzene	33.7	1.2	5.7	ND	ND	ND	ND	ND
1,4-Dichlorobenzene	ND	ND	1.2	0.7	0.6	0.5	0.7	0.7

EXPERIMENT II-B.3.2:


Air Q
28.0 scfm
Air Q
22.0 scfm
Air Q
28.0 scfm
diffuser lateral
L_{in}
G_1
G_2
G_3
L_{out}

Compound	L_{in}	L_1		L_2		L_3		L_{out}
	T=0.5 h (ug/L)	T= 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0.5 h (ug/L)
Dichloromethane	11.0	4.5	7.5	3.3	5.6	2.6	1.9	0.5
Chloroform	6.4	2.1	1.7	ND	1.6	1.0	0.1	0.7
1,1,1-Trichloroethane	2.9	ND	ND	ND	ND	ND	ND	0.2
Trichloroethylene	6.9	ND	ND	ND	0.7	ND	0.5	0.1
Toluene	10.5	ND	ND	ND	0.9	0.8	0.3	0.2
Tetrachloroethylene	15.1	3.4	4.0	2.2	11.8	5.2	5.1	1.2
m/p Xylene	36.5	3.1	2.0	0.8	0.4	0.4	ND	0.1
4-Ethyl Toluene	50.2	0.4	0.2	0.2	0.6	ND	ND	0.3
1,3,5-Trimethylbenzene	5.9	ND	ND	ND	ND	ND	ND	0.2
1,4-Dichlorobenzene	ND	ND	1.2	ND	ND	ND	ND	0.5

APPENDIX A6 - EXPERIMENTAL CONDITIONS AND VOC CONCENTRATION DATA; NON-DOSED WASTEWATER EXPERIMENTS; HIGHLAND CREEK WASTEWATER, 5 DAY SRT

EXPERIMENTAL CONDITIONS:

EXPERIMENT NUMBER	DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
II-C.1.1	FINE	7.20	6.90	23.5	19.0	680
II-C.1.2	FINE	28.6	6.50	24.0	23.0	710
II-C.1.3	FINE	9.50	5.60	16.0	20.5	850
II-C.1.4	FINE	29.1	6.80	18.0	19.5	1020
II-C.1.5	FINE	22.0	6.90	15.0	17.5	1130
II-C.1.6	FINE	9.40	5.40	15.5	18.5	880

Table A6.1 - VOC Concentration Data; Non-Dosed Wastewater Experiment II-C.1.1, Highland Creek Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION B58 (t=24) (ug/L)	B59 (t=24) (ug/L)	B60 (t=25) (ug/L)	B61 (t=26) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION B66 (t=1.5) (ug/L)
Dichloromethane	60.4	74.2	57.4	89.8	70.5	2.7
Chloroform	1.6	4.1	5.8	5.8	4.3	0.3
1,1,1-Trichloroethane	168.2	276.8	241.1	295.9	245.5	13.8
Trichloroethylene	0.9	1.7	1.1	2.1	1.6	ND
Toluene	150.7	169.2	156.8	211.3	172.0	0.6
Tetrachloroethylene	ND	1.2	1.4	1.9	1.1	0.1
p-Xylene	10.5	9.2	8.7	10.1	9.6	ND
4-Ethyl Toluene	25.3	23.2	22.3	21.6	23.1	ND
1,3,5-Trimethylbenzene	11.0	10.4	9.5	9.5	10.1	ND
1,4-Dichlorobenzene	4.3	5.0	6.6	5.8	5.4	0.8
1,1-Dichloroethane	10.7	15.6	14.3	17.6	14.6	10.1

Compound	EFFLUENT CONCENTRATION B62 (t=24) (ug/L)	B63 (t=1) (ug/L)	B64 (t=2) (ug/L)	B65 (t=3) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 57 (ng/L)
Dichloromethane	2.4	3.8	4.0	3.3	3.4	349.7
Chloroform	0.4	0.5	0.5	0.5	0.5	42.3
1,1,1-Trichloroethane	7.2	13.6	14.1	13.9	12.2	2931.9
Trichloroethylene	ND	ND	ND	ND	ND	20.5
Toluene	ND	ND	ND	ND	ND	163.7
Tetrachloroethylene	ND	0.1	0.1	ND	0.1	45.9
p-Xylene	ND	0.2	0.2	ND	0.1	21.4
4-Ethyl Toluene	ND	ND	ND	ND	ND	29.1
1,3,5-Trimethylbenzene	ND	ND	ND	ND	ND	22.1
1,4-Dichlorobenzene	0.8	0.9	0.8	0.8	0.8	162.5
1,1-Dichloroethane	0.6	0.6	0.7	0.6	0.6	107.4

Table A6.2 - VOC Concentration Data; Non-Dosed Wastewater Experiment II-C.1.2, Highland Creek Wastewater, 5 day SRT

	INFLUENT CONCENTRATION					RECYCLE SLUDGE CONCENTRATION
Compound	B83 (t=24) (ug/L)	B84 (t=25) (ug/L)	B85 (t=26) (ug/L)	B86 (t=27) (ug/L)	Avg (ug/L)	B91 (t=25.5) (ug/L)
Dichloromethane	15.9	12.9	14.4	12.5	13.9	1.3
Chloroform	1.6	2.0	2.7	3.2	2.4	0.2
1,1,1-Trichloroethane	39.8	83.2	197.0	288.0	152.0	2.9
Trichloroethylene	ND	ND	1.1	1.1	0.6	ND
Toluene	174.0	127.0	142.0	140.0	145.8	0.5
Tetrachloroethylene	1.3	1.0	1.6	5.5	2.4	ND
p-Xylene	7.1	6.4	8.4	9.1	7.8	ND
4-Ethyl Toluene	13.7	11.3	11.4	12.3	12.2	ND
1,3,5-Trimethylbenzene	6.1	5.2	5.1	5.6	5.5	ND
1,4-Dichlorobenzene	3.0	2.7	2.5	2.6	2.7	0.4
1,1-Dichloroethane	14.9	13.9	17.4	14.3	15.1	1.7

	EFFLUENT CONCENTRATION					OFF-GAS CONCENTRATION		
Compound	B87 (t=0) (ug/L)	B88 (t=1) (ug/L)	B89 (t=2) (ug/L)	B90 (t=3) (ug/L)	Avg (ug/L)	TUBE 45 (ng/L)	TUBE 64 (ng/L)	AVG (ng/L)
Dichloromethane	0.8	1.7	3.2	1.5	1.8	203.0	190.7	196.9
Chloroform	0.2	0.2	0.3	0.2	0.2	7.5	7.0	7.3
1,1,1-Trichloroethane	2.5	2.5	5.0	3.4	3.4	1004.9	1077.9	1041.4
Trichloroethylene	ND	ND	ND	ND	ND	ND	ND	ND
Toluene	ND	ND	ND	ND	ND	104.9	90.5	97.7
Tetrachloroethylene	ND	ND	ND	ND	ND	16.5	15.3	15.9
p-Xylene	ND	ND	ND	ND	ND	17.6	15.4	16.5
4-Ethyl Toluene	ND	ND	ND	ND	ND	7.3	6.7	7.0
1,3,5-Trimethylbenzene	ND	ND	ND	ND	ND	5.7	0.0	2.9
1,4-Dichlorobenzene	0.3	0.3	0.3	0.3	0.3	36.6	33.3	35.0
1,1-Dichloroethane	0.4	0.4	0.4	0.2	0.4	27.5	26.8	27.1

Table A6.3 - VOC Concentration Data; Non-Dosed Wastewater
Experiment II-C.1.3, Highland Creek Wastewater,
5 day SRT

	INFLUENT CONCENTRATION					RECYCLE SLUDGE CONCENTRATION
Compound	B92 (t=24) (ug/L)	B93 (t=25) (ug/L)	B94 (t=26) (ug/L)	B95 (t=3) (ug/L)	Avg (ug/L)	B100 (t=1.5) (ug/L)
Dichloromethane	174.0	126.0	60.7	93.8	113.6	0.5
Chloroform	1.3	2.3	2.9	3.3	2.5	ND
1,1,1-Trichloroethane	50.0	84.9	102.0	101.0	84.5	ND
Trichloroethylene	1.0	1.1	1.2	1.1	1.1	ND
Toluene	168.0	156.0	167.0	165.0	164.0	1.7
Tetrachloroethylene	2.2	2.2	2.2	2.3	2.2	ND
p-Xylene	5.4	7.1	7.7	7.2	6.9	ND
4-Ethyl Toluene	17.1	19.2	18.8	17.7	18.2	ND
1,3,5-Trimethylbenzene	8.2	9.1	8.4	7.9	8.4	ND
1,4-Dichlorobenzene	5.0	6.2	6.0	5.9	5.8	1.1
1,1-Dichloroethane	15.6	22.1	18.6	17.8	18.5	0.3

	EFFLUENT CONCENTRATION					OFF-GAS CONCENTRATION		
Compound	B96 (t=0) (ug/L)	B97 (t=1) (ug/L)	B98 (t=2) (ug/L)	B99 (t=3) (ug/L)	Avg (ug/L)	TUBE 63 (ng/L)	TUBE 76 (ng/L)	AVG (ng/L)
Dichloromethane	2.6	13.6	19.8	10.8	11.7	1450.3	1424.8	1437.6
Chloroform	0.5	0.5	0.5	0.6	0.5	35.8	36.1	36.0
1,1,1-Trichloroethane	1.3	6.2	7.9	8.0	5.8	1391.0	1278.6	1334.6
Trichloroethylene	ND	ND	ND	ND	ND	6.3	5.9	6.1
Toluene	ND	ND	ND	ND	ND	78.0	78.4	78.2
Tetrachloroethylene	0.1	0.2	0.2	0.2	0.2	106.0	109.6	107.8
p-Xylene	ND	ND	ND	0.1	ND	12.9	13.7	13.3
4-Ethyl Toluene	ND	ND	ND	ND	ND	16.9	16.8	16.8
1,3,5-Trimethylbenzene	ND	ND	ND	ND	ND	15.3	16.6	16.0
1,4-Dichlorobenzene	1.0	1.1	1.1	1.1	1.1	80.1	122.9	101.5
1,1-Dichloroethane	0.1	0.2	0.3	0.3	0.2	39.3	33.7	36.5

Table A6.4 - VOC Concentration Data; Non-Dosed Wastewater Experiment II-C.1.4, Highland Creek Wastewater, 5 day SRT

Compound	INFLUENT CONCENTRATION B101 (t=24) (ug/L)	B102 (t=25.5) (ug/L)	B103 (t=27) (ug/L)	Avg (ug/L)	RECYCLE SLUDGE CONCENTRATION B107 (t=25.5) (ug/L)
Dichloromethane	19.9	39.7	123.5	61.0	0.8
Chloroform	1.3	2.0	3.8	2.4	ND
1,1,1-Trichloroethane	51.7	54.9	126.5	77.7	0.7
Trichloroethylene	1.0	0.9	8.6	3.5	ND
Toluene	249.0	181.0	211.0	213.7	0.1
Tetrachloroethylene	1.4	1.5	2.8	1.9	ND
p-Xylene	10.2	10.0	9.0	9.7	ND
4-Ethyl Toluene	18.8	14.6	12.9	15.4	ND
1,3,5-Trimethylbenzene	7.6	5.9	5.7	6.4	ND
1,4-Dichlorobenzene	4.0	4.6	5.1	4.6	0.4
1,1-Dichloroethane	12.3	10.4	14.3	12.3	1.2

Compound	EFFLUENT CONCENTRATION B104 (t=24) (ug/L)	B105 (t=25.5) (ug/L)	B106 (t=27) (ug/L)	Avg (ug/L)	OFF-GAS CONCENTRATION TUBE 17 (ng/L)	TUBE 31 (ng/L)	AVG (ng/L)
Dichloromethane	0.9	2.0	2.8	1.9	318.5	302.2	310.3
Chloroform	0.2	0.3	0.3	0.3	27.1	27.2	27.1
1,1,1-Trichloroethane	1.6	2.6	2.9	2.4	769.2	827.8	798.5
Trichloroethylene	ND	ND	ND	ND	5.4	4.6	5.0
Toluene	ND	ND	0.1	0.0	463.3	499.9	481.6
Tetrachloroethylene	ND	ND	ND	ND	32.3	32.9	32.6
p-Xylene	ND	ND	ND	ND	19.1	20.2	19.7
4-Ethyl Toluene	ND	ND	ND	ND	32.3	33.5	32.9
1,3,5-Trimethylbenzene	ND	ND	ND	ND	19.1	20.0	19.6
1,4-Dichlorobenzene	0.4	0.5	0.5	0.5	85.5	87.0	86.3
1,1-Dichloroethane	0.2	0.2	0.2	0.2	31.2	31.4	31.3

Table A6.5 - VOC Concentration Data; Non-Dosed Wastewater Experiment II-C.1.5, Highland Creek Wastewater, 5 day SRT

	INFLUENT CONCENTRATION				RECYCLE SLUDGE CONCENTRATION
Compound	B108 (t=24) (ug/L)	B109 (t=25.5) (ug/L)	B110 (t=27) (ug/L)	Avg (ug/L)	B114 (t=1.5) (ug/L)
Dichloromethane	30.3	56.1	64.9	50.4	0.4
Chloroform	1.6	1.7	2.7	2.0	ND
1,1,1-Trichloroethane	59.9	102.0	135.0	99.0	ND
Trichloroethylene	0.9	1.2	1.3	1.1	ND
Toluene	180.0	125.0	157.0	154.0	ND
Tetrachloroethylene	0.9	1.6	2.6	1.7	ND
p-Xylene	5.7	5.4	6.5	5.9	ND
4-Ethyl Toluene	7.1	8.6	9.4	8.4	ND
1,3,5-Trimethylbenzene	3.2	3.7	4.0	3.6	ND
1,4-Dichlorobenzene	4.5	4.8	5.3	4.9	ND
1,1-Dichloroethane	4.8	5.1	5.7	5.2	0.5

	EFFLUENT CONCENTRATION				OFF-GAS CONCENTRATION		
Compound	B111 (t=24) (ug/L)	B112 (t=25.5) (ug/L)	B113 (t=27) (ug/L)	Avg (ug/L)	TUBE 34 (ng/L)	TUBE 44 (ng/L)	Avg (ng/L)
Dichloromethane	1.3	2.0	4.2	2.5	301.2	311.3	306.3
Chloroform	0.3	0.3	0.3	0.3	21.0	21.3	21.2
1,1,1-Trichloroethane	2.9	3.4	4.6	3.6	1194.2	1162.2	1178.2
Trichloroethylene	ND	ND	ND	ND	6.6	6.1	6.4
Toluene	ND	ND	ND	ND	429.1	88.2	258.7
Tetrachloroethylene	ND	ND	ND	ND	37.6	39.7	38.7
p-Xylene	ND	ND	ND	ND	9.3	5.9	7.6
4-Ethyl Toluene	ND	ND	ND	ND	12.7	10.4	11.6
1,3,5-Trimethylbenzene	ND	ND	ND	ND	7.6	6.8	7.2
1,4-Dichlorobenzene	0.5	0.5	0.5	0.5	86.2	86.0	86.1
1,1-Dichloroethane	0.4	0.4	0.4	0.4	67.5	65.0	66.3

Table A6.6 - VOC Concentration Data; Non-Dosed Wastewater
Experiment II-C.1.6, Highland Creek Wastewater,
5 day SRT

	INFLUENT CONCENTRATION				RECYCLE SLUDGE CONCENTRATION
Compound	B127 (t=24) (ug/L)	B128 (t=25.5) (ug/L)	B129 (t=27) (ug/L)	Avg (ug/L)	B133 (t=1.5) (ug/L)
Dichloromethane	59.6	69.6	130.0	86.4	6.7
Chloroform	2.7	3.0	3.3	3.0	0.1
1,1,1-Trichloroethane	31.1	51.1	76.6	52.9	0.8
Trichloroethylene	1.2	1.0	1.3	1.2	ND
Toluene	41.0	70.9	52.1	54.7	1.8
Tetrachloroethylene	4.2	4.5	11.1	6.6	0.7
p-Xylene	6.5	6.3	5.8	6.2	ND
4-Ethyl Toluene	7.7	8.0	7.5	7.7	ND
1,3,5-Trimethylbenzene	3.7	3.8	3.5	3.7	ND
1,4-Dichlorobenzene	3.9	4.1	3.8	3.9	1.0
1,1-Dichloroethane	5.0	6.3	7.1	6.1	2.9

	EFFLUENT CONCENTRATION				OFF-GAS CONCENTRATION		
Compound	B130 (t=24) (ug/L)	B131 (t=25.5) (ug/L)	B132 (t=27) (ug/L)	Avg (ug/L)	TUBE 65 (ng/L)	TUBE 90 (ng/L)	Avg (ng/L)
Dichloromethane	6.3	5.1	6.3	5.9	1040.8	1000.5	1020.7
Chloroform	1.0	1.1	0.9	1.0	100.4	97.4	98.9
1,1,1-Trichloroethane	4.2	4.7	4.8	4.6	1312.9	1259.4	1286.2
Trichloroethylene	ND	ND	ND	0.0	13.8	12.0	12.9
Toluene	ND	ND	ND	0.0	144.7	134.5	139.6
Tetrachloroethylene	0.6	0.7	0.6	0.6	402.6	390.2	396.4
p-Xylene	ND	ND	ND	0.0	12.3	11.9	12.1
4-Ethyl Toluene	ND	ND	ND	0.0	4.8	13.1	9.0
1,3,5-Trimethylbenzene	ND	ND	ND	0.0	8.4	8.0	8.2
1,4-Dichlorobenzene	1.2	0.9	0.9	1.0	158.0	157.9	158.0
1,1-Dichloroethane	0.8	0.8	0.6	0.7	112.8	109.8	111.3

APPENDIX A7-EXPERIMENTAL CONDITIONS AND VOC CONCENTRATION DATA; PARALLEL PILOT PLANT/FULL SCALE AERATION BASIN EXPERIMENTS; HIGHLAND CREEK WASTEWATER

PILOT PLANT SAMPLING: Parallel Full Scale Aeration Basin/Pilot Plant Experiment II-C.2.1

PILOT PLANT CONDITIONS:

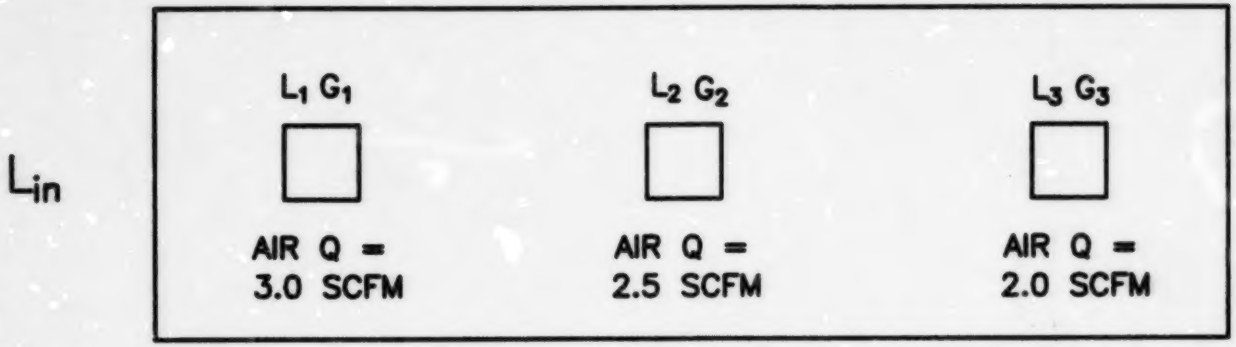
DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
FINE	7.24	6.80	21.0	22.5	490

RESULTS:

	INFLUENT CONCENTRATION			RECYCLE SLUDGE CONCENTRATION
Compound	B70 (t=24) (ug/L)	B71 (t=25.5) (ug/L)	Avg (ug/L)	B82 (t=25.5) (ug/L)
Dichloromethane	55.5	37.7	46.6	1.7
Chloroform	3.0	4.5	3.8	0.5
1,1,1-Trichloroethane	210.0	264.0	237.0	21.0
Trichloroethylene	1.9	0.9	1.4	ND
Toluene	179.0	122.0	150.0	ND
Tetrachloroethylene	7.8	5.6	6.7	1.2
p-Xylene	43.2	42.3	42.8	ND
4-Ethyl Toluene	19.3	20.1	19.7	ND
1,3,5-Trimethylbenzene	8.9	10.2	9.6	ND
1,4-Dichlorobenzene	5.3	5.3	5.3	1.2

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	B74 (t=24) (ug/L)	B75 (t=25.5) (ug/L)	Avg (ug/L)	TUBE 18 (ng/L)	TUBE 58 (ng/L)	Avg (ng/L)
Dichloromethane	2.1	2.8	2.5	401.9	446.2	424.0
Chloroform	0.4	0.5	0.5	51.6	55.1	53.4
1,1,1-Trichloroethane	8.5	14.6	11.6	5286.5	5380.4	5333.4
Trichloroethylene	ND	ND	0.0	27.8	29.9	28.9
Toluene	ND	ND	0.0	178.0	205.3	191.6
Tetrachloroethylene	0.7	0.7	0.7	771.2	833.6	802.4
p-Xylene	ND	ND	0.0	33.9	93.0	63.5
4-Ethyl Toluene	ND	ND	0.0	26.1	31.5	28.8
1,3,5-Trimethylbenzene	ND	ND	0.0	24.0	26.1	25.1
1,4-Dichlorobenzene	1.0	1.0	1.0	179.3	171.5	175.4

EXPERIMENT II-C.2.1; Full Scale Data



Compound	L_{in}	L_1		L_2		L_3		G_1	G_2	G_3
	T=0.5 h (ug/L)	T= 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	(ng/L)	(ng/L)	(ng/L)
Dichloromethane	32.7	7.1	3.3	2.8	2.1	1.8	3.0	459.7	195.6	152.5
Chloroform	2.7	0.7	0.6	0.4	0.5	0.4	0.5	57.6	32.4	29.2
1,1,1-Trichloroethane	226.3	44.5	52.9	18.0	30.0	12.9	36.1	6588.4	3950.0	3682.6
Trichloroethylene	1.0	ND	ND	ND	ND	ND	ND	35.3	15.1	9.4
Toluene	121.0	ND	ND	ND	ND	ND	ND	267.7	107.1	91.5
Tetrachloroethylene	5.5	1.6	0.9	0.9	0.8	0.7	0.9	1086.7	770.6	792.4
m/p Xylene	41.5	0.4	0.5	ND	ND	ND	ND	225.1	27.6	14.6
4-Ethyl Toluene	18.6	0.1	0.1	ND	ND	ND	ND	56.1	8.0	ND
1,3,5-Trimethylbenzene	9.0	ND	ND	ND	ND	ND	ND	42.9	8.4	ND
1,4-Dichlorobenzene	4.8	1.4	1.4	1.3	1.2	1.1	1.3	241.3	133.8	158.4

PILOT PLANT SAMPLING: Parallel Full Scale Aeration Basin/Pilot Plant Experiment II-C.2.2

PILOT PLANT CONDITIONS:

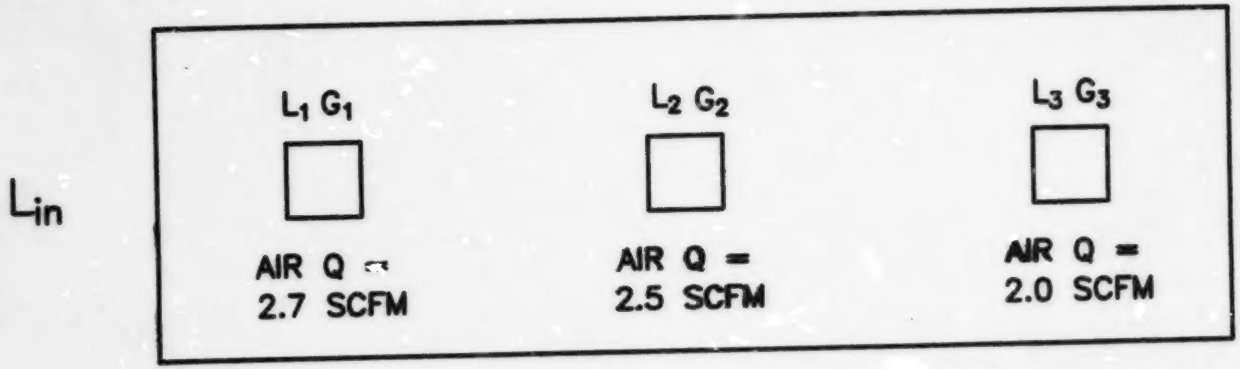
DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
FINE	7.28	6.50	14.5	18.5	815

RESULTS:

	INFLUENT CONCENTRATION		
Compound	B123 (t=24) (ug/L)	B124 (t=25.5) (ug/L)	Avg (ug/L)
Dichloromethane	58.7	201.0	129.9
Chloroform	2.7	3.5	3.1
1,1,1-Trichloroethane	118.0	179.0	148.5
Trichloroethylene	14.0	14.3	14.2
Toluene	310.0	330.0	320.0
Tetrachloroethylene	1.2	1.4	1.3
p-Xylene	10.0	13.8	11.9
4-Ethyl Toluene	6.7	9.0	7.9
1,3,5-Trimethylbenzene	3.2	4.7	3.9
1,4-Dichlorobenzene	4.3	4.3	4.3

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	B125 (t=24) (ug/L)	B126 (t=25.5) (ug/L)	Avg (ug/L)	TUBE 52 (ng/L)	TUBE 96 (ng/L)	Avg (ng/L)
Dichloromethane	3.3	3.2	3.3	331.2	368.3	349.7
Chloroform	0.8	0.6	0.7	67.9	56.4	62.1
1,1,1-Trichloroethane	8.1	11.1	9.6	2258.2	2308.1	2283.1
Trichloroethylene	ND	ND	ND	104.8	113.9	109.3
Toluene	ND	ND	ND	503.5	582.4	542.9
Tetrachloroethylene	0.2	0.2	0.2	75.7	86.8	81.3
p-Xylene	ND	ND	0.0	12.4	15.4	13.9
4-Ethyl Toluene	ND	ND	0.0	11.1	12.2	11.7
1,3,5-Trimethylbenzene	ND	ND	0.0	ND	7.0	3.5
1,4-Dichlorobenzene	0.7	0.8	0.8	117.3	132.7	125.0

EXPERIMENT II-C.2.2; Full Scale Data



Compound	L_{in}	L_1		L_2		L_3		G_1	G_2	G_3
	T=0.5 h (ug/L)	T= 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	(ng/L)	(ng/L)	(ng/L)
Dichloromethane	66.9	4.1	8.0	1.6	2.5	1.0	1.8	505.8	153.4	110.8
Chloroform	2.6	0.5	0.8	0.5	0.5	0.5	0.7	66.5	42.0	36.7
1,1,1-Trichloroethane	119.5	13.1	24.1	9.4	11.5	8.6	14.2	4944.0	3227.4	2982.6
Trichloroethylene	10.3	0.8	1.6	0.2	0.7	ND	0.6	415.9	183.8	90.3
Toluene	240.0	1.5	1.7	0.4	0.5	0.1	0.2	539.5	951.7	944.1
Tetrachloroethylene	0.6	0.2	0.3	0.2	0.3	0.2	0.3	115.3	104.4	96.4
m/p Xylene	9.8	0.3	0.4	ND	ND	ND	ND	87.1	20.7	ND
4-Ethyl Toluene	6.9	0.1	0.2	ND	ND	ND	ND	47.1	17.3	ND
1,3,5-Trimethylbenzene	3.3	ND	0.1	ND	ND	ND	ND	31.9	9.2	ND
1,4-Dichlorobenzene	4.3	1.2	1.2	1.1	1.2	1.0	1.1	226.5	163.1	202.7

PILOT PLANT SAMPLING: Parallel Full Scale Aeration Basin/Pilot Plant Experiment II-C.2.3

PILOT PLANT CONDITIONS:

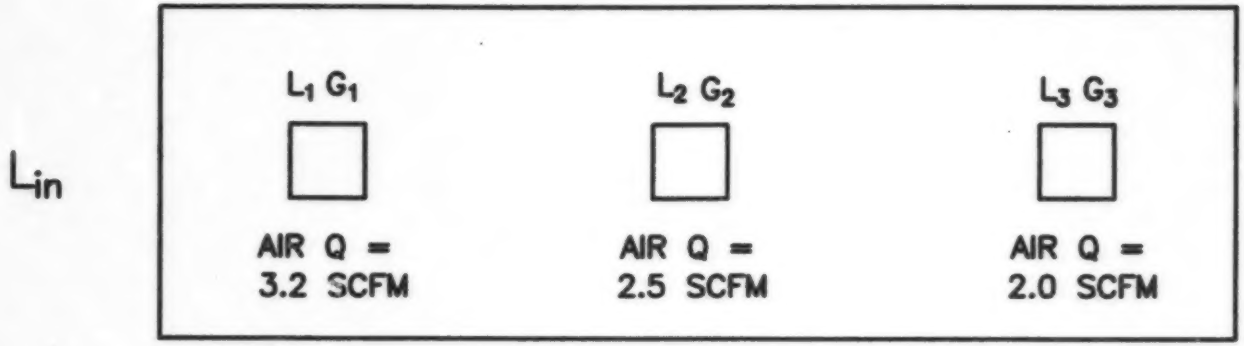
DIFFUSER TYPE	AIRFLOW RATE (SCFM)	AIR PRESSURE (psig)	AIR TEMPERATURE (C)	MIXED LIQUOR TEMPERATURE (C)	OFF-GAS SAMPLE VOLUME (mL)
FINE	7.24	5.40	17.5	19.0	1190

RESULTS:

	INFLUENT CONCENTRATION		
Compound	B142 (t=0) (ug/L)	B143 (t=1.5) (ug/L)	Avg (ug/L)
Dichloromethane	54.3	28.6	41.5
Chloroform	2.5	3.6	3.1
1,1,1-Trichloroethane	90.3	172.0	131.2
Trichloroethylene	1.9	1.8	1.9
Toluene	165.0	7.2	86.1
Tetrachloroethylene	16.1	11.7	13.9
p-Xylene	17.3	12.7	15.0
4-Ethyl Toluene	15.4	12.9	14.2
1,3,5-Trimethylbenzene	6.6	6.8	6.7
1,4-Dichlorobenzene	4.1	5.1	4.6

	EFFLUENT CONCENTRATION			OFF-GAS CONCENTRATION		
Compound	B144 (t=0) (ug/L)	B145 (t=1.5) (ug/L)	Avg (ug/L)	TUBE 52 (ng/L)	TUBE 96 (ng/L)	Avg (ng/L)
Dichloromethane	4.6	3.9	4.3	608.3	566.3	587.3
Chloroform	0.9	0.9	0.9	101.7	27.9	64.8
1,1.1-Trichloroethane	9.8	11.4	10.6	2239.0	2166.7	2202.8
Trichloroethylene	ND	ND	ND	21.8	21.2	21.5
Toluene	ND	ND	ND	145.1	135.4	140.3
Tetrachloroethylene	2.3	2.0	2.2	946.8	884.1	915.4
p-Xylene	ND	ND	ND	21.9	21.3	21.6
4-Ethyl Toluene	ND	ND	ND	21.9	21.0	21.5
1,3,5-Trimethylbenzene	ND	ND	ND	14.6	13.7	14.2
1,4-Dichlorobenzene	0.9	0.9	0.9	174.4	163.7	169.1

EXPERIMENT II-C.2.3; Full Scale Data



Compound	L_{in}	L_1		L_2		L_3		G_1	G_2	G_3
	T=0.5 h (ug/L)	T= 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	T = 0 h (ug/L)	T = 1 h (ug/L)	(ng/L)	(ng/L)	(ng/L)
Dichloromethane	21.8	1.6	2.2	1.0	1.5	1.4	1.1	162.1	128.9	120.0
Chloroform	2.6	0.5	0.5	0.4	0.4	0.4	0.3	48.0	44.7	45.2
1,1,1-Trichloroethane	121.1	11.1	19.5	9.8	13.0	6.9	13.5	3344.3	2277.3	2190.6
Trichloroethylene	1.3	0.2	0.2	ND	ND	ND	ND	51.6	41.7	42.5
Toluene	50.4	0.1	0.1	0.2	ND	ND	ND	344.4	146.6	88.6
Tetrachloroethylene	8.3	1.3	1.3	1.3	1.0	1.0	0.9	860.3	652.8	663.7
m/p Xylene	15.4	0.5	0.3	0.2	ND	ND	ND	123.7	59.5	25.1
4-Ethyl Toluene	15.2	0.3	0.2	0.2	ND	ND	ND	90.5	46.4	22.5
1,3,5-Trimethylbenzene	6.8	0.2	0.1	0.1	ND	ND	ND	61.5	33.6	19.8
1,4-Dichlorobenzene	4.3	1.3	1.2	1.2	1.2	1.2	1.1	233.3	213.5	223.1

APPENDIX C

Liquid Sample Analysis Quality Assurance/Quality Control

Table C.1- Reported Method Detection Limit For Each Candidate VOC in Liquid Samples

	Laboratory		
	WTC	Barringer	Canviro
	Method Detection Limit (ug/L)		
Dichloromethane	1.0	0.5	1.8
Chloroform	1.0	0.2	0.4
Trichloroethylene	1.0	0.2	1.9
1,1,1-Trichloroethane	1.0	0.2	0.5
Toluene	1.0	0.2	0.7
Tetrachloroethylene	1.0	0.5	0.8
p-Xylene	1.0	0.2	0.6
4-Ethyl Toluene	1.0	0.1	2.9
1,3,5-Trimethylbenzene	1.0	0.1	0.7
1,4-Dichlorobenzene	1.0	0.2	0.1

Table C.2- Recovery of Surrogate Compounds

PHASE A DOSED TAP WATER EXPERIMENTS

Exper Number	Pilot Plant Influent Samples			Pilot Plant Effluent Samples		
	Sample Number	Surrogate* Recovery (%)		Sample Number	Surrogate* Recovery (%)	
		WS1	WS2		WS1	WS2
II-A.1	W3	94		W5	100	
	W4	58		W6	40	
	W8	48				
II-A.2	W11	49	69	W13	110	58
	W12	53	49	W14	110	79
	W16	125	78			
II-A.3	W19	116	50			
	W20	100	71	W21	107	45
	W24	110	60	W22	95	58
II-A.4	W28	75	94	W31	83	82
	W29	84	95	W32	75	83
	W30	83	105			
II-A.5	W33	102	112	W37	100	111
	W34	94	93	W38	93	85
	W35	83	76	W39	95	77
	W36	99	98	W40	102	82

*- WS1= C_6H_5F
WS2= 1-Fluorononane

continued

Table C.2 Continued- Recovery of Surrogate Compounds

	Pilot Plant Influent Samples				Pilot Plant Effluent Samples			
	Sample Number	Surrogate* Recovery (%)			Sample Number	Surrogate* Recovery (%)		
		WS1	WS2			WS1	WS2	
	W41	113	100		W45	93	77	
II-A.6	W42	106	118		W46	85	70	
	W43	102	104		W47	103	89	
	W44	93	84		W48	94	85	
		BS1	BS2	BS3		BS1	BS2	BS3
	B50	156	142	92	B52	110	90	100
II-A.7	B51	156	156	89	B53	93	92	96
	B54	91	80	99	B56	115	108	94
	B55	119	106	91	B57	90	84	85
		S1	S2	S3		S1	S2	S3
II-A.8	S54	93	97	74	S56	75	76	68
	S55	91	88	69	S57	82	64	100

*- WS1- C_6H_5F
WS2- 1-Fluorononane
WS3- 1,2-Dibromo 4,5-Difluorobenzene
BS1- 1-Chloro-2-bromopropane
BS2 1,4-Dichlorobutane
BS3 4-Bromofluorobenzene

continued

Table C.2 Continued- Recovery of Surrogate Compounds

PILOT PLANT EXPERIMENTS EMPLOYING BURLINGTON WASTEWATER

	Pilot Plant Influent Samples				Pilot Plant Effluent Samples				Pilot Plant RAS Samples			
	Sample Number	Surrogate* Recovery (%)			Sample Number	Surrogate* Recovery (%)			Sample Number	Surrogate* Recovery (%)		
		WS1	WS2	WS3		WS1	WS2	WS3		WS1	WS2	WS3
		---	---	---		---	---	---		---	---	---
II-B.1.1	W54	93	97	74	W57	82	64	100				
	W55	91	88	69	W58	87	67	92				
	W56	75	76	68	W59	73	53	65	W60	133	75	93
II-B.1.2	W61	122	71	81	W64	99	41	83	W67	84	58	53
	W62	71	99	109	W65	88	65	83				
	W63	93	98	74	W66	96	69	96				
II-B.1.3	W68	112	114	128	W71	91	79	97	W74	87	71	117
	W69	59	49	55	W72	110	81	96				
	W70	104	81	107	W73	94	83	121				
II-B.1.4	W75	72	94	74	W78	84	63	75	W81	63	37	52
	W76	56	50	48	W79	74	47	56				
	W77	75	78	70	W80	59	39	46				
II-B.1.5	W82	81	85	62	W84	83	46	63	W86	75	40	48
	W83	74	72	64	W85	81	36	64				
II-B.1.6	W87	85	104	86	W89	86	50	69	W91	80	47	59
	W88	78	58	66	W90	79	46	79				

*- WS1- C_6H_5F
WS2- 1-Fluorononane
WS3- 1,2-Dibromo 4,5-Difluorobenzene

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continued

Table C.2 Continued- Recovery of Surrogate Compounds

	Pilot Plant Influent Samples					Pilot Plant Effluent Samples					Pilot Plant RAS Samples				
	Sample Number	Surrogate* Recovery (%)				Sample Number	Surrogate* Recovery (%)				Sample Number	Surrogate* Recovery (%)			
		WS1	WS2	WS3			WS1	WS2	WS3			WS1	WS2	WS3	
II-B.1.7	W97	106	102	81		W99	69	42	65		W101	43	40	37	
	W98	77	74	74		W100	55	30	54						
		CS1	CS2	CS3	CS4		CS1	CS2	CS3	CS4		CS1	CS2	CS3	CS4
II-B.1.8	C40	88	109	88	105	C42	86	133	79	114	C44	66	82	87	91
	C41	81	138	88	110	C43	91	96	88	94					
		BS1	BS2	BS3			BS1	BS2	BS3			BS1	BS2	BS3	
II-B.2.1	B1	106	100	96		B4	105	120	99		B7	---	122	104	
	B3	119	108	102		B6	100	93	92						
II-B.2.2	B8	112	115	109		B10	109	111	104		B12	106	114	97	
	B9	107	116	103		B11	105	105	98						

*- WS1- C_6H_5F
WS2- 1-Fluorononane
WS3- 1,2-Dibromo 4,5-Difluorobenzene
CS1- d5-Bromomethane
CS2- d4-1,2-Dichloroethane
CS3- d-Toluene
CS4- 4-Bromofluorobenzene
BS1- 1-Chloro-2-Bromopropane
BS2- 1,4-Dichlorobutane
BS3- 4- Bromofluorobenzene

continued

Table C.2 Continued- Recovery of Surrogate Compounds

PILOT PLANT EXPERIMENTS EMPLOYING HIGHLAND CREEK WASTEWATER

	Pilot Plant Influent Samples				Pilot Plant Effluent Samples				Pilot Plant RAS Samples			
	Sample Number	Surrogate[*] Recovery (%)			Sample Number	Surrogate[*] Recovery (%)			Sample Number	Surrogate[*] Recovery (%)		
		BS1	BS2	BS3		BS1	BS2	BS3		BS1	BS2	BS3
		---	---	---		---	---	---		---	---	---
II-C.1.1	B58	122	108	93	B62	114	115	89	B66	133	123	85
	B59	145	131	90	B63	103	106	87				
	B60	97	84	101	B64	96	106	80				
	B61	147	125	89	B65	86	100	77				
II-C.1.2	B83	125	112	95	B87	91	89	92	B91	88	75	101
	B84	92	92	91	B88	125	120	92				
	B85	89	90	93	B89	114	133	82				
	B86	91	89	92	B90	86	93	80				
II-C.1.3	B92	102	96	107	B96	86	89	104	B100	104	98	98
	B93	91	94	98	B97	83	88	95				
	B94	89	95	97	B98	84	91	92				
	B95	91	104	89	B99	77	88	89				
II-C.1.4	B101	124	102	97	B104	99	92	93	B107	92	95	91
	B102	109	99	89	B105	109	91	106				
	B103	116	107	92	B106	91	85	95				
II-C.1.5	B108	119	94	97	B111	96	75	94	B114	113	130	77
	B109	105	91	88	B112	91	72	90				
	B110	115	94	93	B113	85	73	82				

[*]- BS1- 1-Chloro-2-Bromopropane
BS2- 1,4-Dichlorobutane
BS3- 4- Bromofluorobenzene

continued

Table C.2 Continued- Recovery of Surrogate Compounds

	Pilot Plant Influent Samples				Pilot Plant Effluent Samples				Pilot Plant RAS Samples			
	Sample Number	Surrogate* Recovery (%)			Sample Number	Surrogate* Recovery (%)			Sample Number	Surrogate* Recovery (%)		
		BS1	BS2	BS3		BS1	BS2	BS3		BS1	BS2	BS3
II-C.1.6	B127	79	87	73	B130	176	113	85	B133	207	122	84
	B128	86	94	66	B131	95	117	78				
	B129	36	92	75	B132	79	98	66				
II-C.2.1	B70	98	104	78	B74	78	79	72	B82	101	91	94
	B71	78	78	80	B75	76	81	67				
II-C.2.2	B123	188	101	100	B125	115	136	82				
	B124	185	103	100	B126	111	118	95				
II-C.2.3	B142	77	94	91	B144	80	101	78				
	B143	76	100	44	B145	80	103	67				

APPENDIX D

Summary of Mass Balance Closure Results For Each Pilot Plant Experiment

Table D.1 - Mass Balance Closure Results; Dichloromethane

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	53.2	NA	30.7	83.9	16.1
II.A.2	65.8	NA	59.1	124.9	-24.9
II.A.3	18.4	NA	92.7	111.1	-11.1
II.A.4	29.9	NA	91.1	121.0	-21.0
II.A.5	54.4	NA	79.7	134.1	-34.1
II.A.6	39.5	NA	3.4	43.0	57.0
II.A.7	85.1	NA	38.8	123.9	-23.9
II.A.8	29.8	NA	57.1	86.9	13.1

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	21.9	0.0	26.2	48.1	51.9
II.B1.2	52.5	0.8	26.9	80.2	19.8
II.B1.3	37.0	0.7	39.3	77.0	23.0
II.B1.4	91.1	0.7	16.0	107.9	- 7.9
II.B1.5	9.8	0.1	15.1	25.0	75.0
II.B1.6	20.6	2.1	29.8	52.5	47.5
II.B1.7	32.6	0.0	9.5	42.2	57.8
II.B1.8	220.2	0.5	43.6	264.3	-164.3
II.B1.9	14.5	0.1	5.9	20.5	79.5
II.B1.10	29.6	0.0	2.4	32.0	68.0

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	32.9	0.1	10.4	43.4	56.6
II.B2.2	74.7	0.0	0.0	74.6	25.4
II.B2.3	68.1	0.0	13.7	81.8	18.2
II.B2.4	25.6	0.1	13.2	39.0	61.0
II.B2.5	12.8	0.1	23.5	36.4	63.6

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	7.5	0.0	4.8	12.3	87.6
II.C1.2	84.6	0.1	12.9	97.7	2.3
II.C1.3	25.0	0.0	10.3	35.3	64.7
II.C1.4	30.9	0.0	3.1	34.0	66.0
II.C1.5	27.9	0.0	5.0	32.9	67.1
II.C1.6	23.2	0.1	6.8	30.1	69.8
II.C2.1	13.7	0.4	5.5	19.1	80.9
II.C2.2	4.1	0.0	2.5	6.6	93.3
II.C2.3	20.8	0.0	10.4	31.2	68.8

Table D.2 - Mass Balance Closure Summary; Chloroform

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	106.8	0.0	36.2	143.0	- 43.0
II.A.2	23.4	0.0	57.5	81.0	19.0
II.A.3	14.0	0.0	15.6	29.6	70.4
II.A.4	34.0	0.0	65.8	99.9	0.2
II.A.5	27.2	0.0	39.1	66.4	33.6
II.A.6	37.0	0.0	106.6	143.6	- 43.6
II.A.7	38.6	0.0	12.2	50.7	49.3
II.A.8	24.8	0.0	41.7	66.5	33.5

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	13.7	0.4	36.6	50.8	49.2
II.B1.2	24.0	0.0	14.3	38.4	61.6
II.B1.3	64.3	0.1	76.8	141.2	- 41.2
II.B1.4	76.8	0.0	13.2	90.1	9.9
II.B1.5	34.7	0.3	39.1	74.1	25.9
II.B1.6	34.7	0.8	26.1	60.8	39.2
II.B1.7	34.0	0.0	8.7	42.8	57.2
II.B1.8	27.5	0.2	26.9	54.7	45.3
II.B1.9	34.3	0.0	24.2	58.6	41.4
II.B1.10	33.3	0.1	6.0	39.4	60.6

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	32.9	0.1	10.4	43.4	56.6
II.B2.2	31.7	0.2	16.3	48.2	51.8
II.B2.3	47.0	0.1	16.4	63.5	36.5
II.B2.4	18.3	0.2	18.2	36.7	63.3
II.B2.5	25.5	0.1	16.3	41.9	58.1

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	14.8	0.1	11.6	26.5	73.5
II.C1.2	18.2	0.1	8.3	26.6	73.4
II.C1.3	28.5	0.0	20.0	48.5	51.5
II.C1.4	68.6	0.0	12.5	81.2	18.9
II.C1.5	48.7	0.1	15.0	63.7	36.3
II.C1.6	64.9	0.0	33.3	98.2	1.8
II.C2.1	21.1	0.1	13.2	34.4	65.6
II.C2.2	30.5	0.0	22.6	53.1	46.9
II.C2.3	31.8	0.0	30.0	61.8	38.2

Table D.3 - Mass Balance Closure Results; 1,1,1-Trichloroethane

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	119.7	0.0	42.9	162.5	-62.5
II.A.2	60.9	0.0	35.5	96.4	3.6
II.A.3	48.5	0.0	13.8	62.3	37.7
II.A.4	49.2	0.0	18.8	68.0	32.0
II.A.5	87.2	0.0	23.7	110.9	-10.9
II.A.6	57.6	0.0	28.9	86.5	13.5
II.A.7	31.3	0.0	4.8	36.2	63.8
II.A.8	46.5	0.0	17.7	64.2	35.8

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	3.2	0.1	0.5	3.7	96.3
II.B1.2	15.5	0.2	21.8	37.3	62.7
II.B1.3	18.7	0.1	6.6	25.3	74.7
II.B1.4	36.5	0.1	8.0	44.6	55.4
II.B1.5	47.3	0.1	30.1	77.4	22.6
II.B1.6	85.1	0.1	22.4	107.6	- 7.6
II.B1.7	31.1	0.2	4.8	36.1	63.9
II.B1.8	27.0	0.1	20.2	47.3	52.7
II.B1.9	76.5	0.1	5.4	82.0	18.0
II.B1.10	27.0	0.1	6.1	33.2	66.8

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	58.1	0.2	8.2	66.5	33.5
II.B2.2	61.5	0.1	8.8	70.3	29.7
II.B2.3	43.5	0.1	17.6	61.3	38.7
II.B2.4	42.6	0.1	9.2	51.9	48.1
II.B2.5	26.0	0.0	4.5	30.6	69.4

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	18.0	0.1	5.0	23.0	77.0
II.C1.2	40.9	0.0	2.2	43.2	56.8
II.C1.3	31.2	0.0	6.9	38.1	61.9
II.C1.4	62.4	0.0	3.1	65.5	34.5
II.C1.5	54.7	0.0	3.6	58.3	41.7
II.C1.6	47.8	0.0	8.7	56.6	43.4
II.C2.1	33.8	0.1	4.9	38.8	61.2
II.C2.2	23.4	0.0	6.5	29.9	70.1
II.C2.3	24.7	0.0	8.1	32.8	67.2

Table D.4 - Mass Balance Closure Summary; Trichloroethylene

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.A.1	58.8	0.0	22.3	81.1	18.9
II.A.2	20.7	0.0	30.9	51.5	48.5
II.A.3	15.4	0.0	6.1	21.5	78.5
II.A.4	87.3	0.0	30.2	117.6	-17.6
II.A.5	50.8	0.0	35.3	86.1	13.9
II.A.6	50.8	0.0	54.7	105.5	-5.5
II.A.7	75.1	0.0	7.6	82.8	17.2
II.A.8	40.0	0.0	28.1	68.0	32.0

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.B1.1	12.7	0.0	1.7	14.4	85.6
II.B1.2	29.0	0.0	2.5	31.6	68.4
II.B1.3	29.8	0.1	12.5	42.3	57.7
II.B1.4	132.1	0.1	7.9	140.1	-40.1
II.B1.5	80.0	0.3	27.1	107.3	- 7.3
II.B1.6	72.6	0.2	17.0	89.9	10.1
II.B1.7	50.0	0.0	5.4	55.4	44.6
II.B1.8	31.0	0.1	14.2	45.3	54.7
II.B1.9	40.3	0.0	9.5	49.8	50.2
II.B1.10	78.9	0.1	6.7	85.7	14.3

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.B2.1	68.7	0.0	6.3	75.0	25.0
II.B2.2	56.4	0.1	5.0	61.4	38.6
II.B2.3	95.1	0.2	6.0	101.3	-1.3
II.B2.4	47.1	0.2	13.1	60.4	39.6
II.B2.5	15.0	0.1	7.7	22.8	77.2

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.C1.1	19.3	0.0	0.0	19.3	80.7
II.C1.2	0.0	0.0	0.0	0.0	100.0
II.C1.3	11.0	0.0	0.0	11.0	89.0
II.C1.4	8.7	0.0	0.0	8.7	91.3
II.C1.5	26.7	0.0	0.0	26.7	73.3
II.C1.6	21.2	0.0	0.0	21.2	78.8
II.C2.1	31.0	0.0	0.0	31.0	69.0
II.C2.2	14.2	0.0	0.0	14.2	85.8
II.C2.3	16.6	0.0	0.0	16.6	83.4

Table D.5 - Mass Balance Closure Summary; Toluene

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	49.6	NA	23.1	72.6	27.4
II.A.2	22.6	NA	38.5	61.0	39.0
II.A.3	93.5	NA	61.8	155.3	-55.3
II.A.4	20.5	NA	37.6	58.1	41.9
II.A.5	37.7	NA	33.1	70.8	29.2
II.A.6	27.3	NA	42.9	70.2	29.8
II.A.7	66.1	NA	4.9	70.9	29.1
II.A.8	29.5	NA	27.0	56.5	43.5

Burlington Skyway Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	NA	NA	1.1	NA	NA
II.B1.2	NA	NA	1.1	NA	NA
II.B1.3	NA	NA	1.4	NA	NA
II.B1.4	NA	NA	1.3	NA	NA
II.B1.5	NA	NA	0.4	NA	NA
II.B1.6	NA	NA	4.4	NA	NA
II.B1.7	NA	NA	2.0	NA	NA
II.B1.8	NA	NA	37.5	NA	NA
II.B1.9	NA	NA	0.9	NA	NA
II.B1.10	NA	NA	3.7	NA	NA

Burlington Skyway Wastewater; 10 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	13.7	0.1	2.1	16.0	84.0
II.B2.2	6.4	0.0	5.0	11.4	88.6
II.B2.3	12.1	0.0	0.0	12.1	87.9
II.B2.4	4.8	0.0	0.0	4.8	95.2
II.B2.5	2.9	0.0	0.0	2.9	97.1

Highland Creek Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	1.4	0.0	0.0	1.4	98.6
II.C1.2	4.0	0.0	0.0	4.0	96.0
II.C1.3	0.9	0.0	0.0	1.0	99.0
II.C1.4	13.7	0.0	0.0	13.7	86.3
II.C1.5	7.7	0.0	0.0	7.7	92.3
II.C1.6	5.0	0.0	0.0	5.1	94.9
II.C2.1	1.9	0.0	0.0	1.9	98.1
II.C2.2	2.6	0.0	0.0	2.6	97.4
II.C2.3	2.4	0.0	0.0	2.4	97.6

Table D.6 - Mass Balance Closure Results; Tetrachloroethylene

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	173.1	NA	45.9	219.1	-119.1
II.A.2	36.0	NA	36.4	72.5	27.5
II.A.3	43.6	NA	36.7	80.3	19.6
II.A.4	56.9	NA	28.6	85.5	14.5
II.A.5	117.4	NA	26.7	144.1	- 44.1
II.A.6	133.1	NA	52.5	185.6	- 85.6
II.A.7	96.7	NA	4.9	101.6	- 1.6
II.A.8	82.8	NA	16.9	99.7	0.2

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	25.6	0.1	4.1	29.8	70.2
II.B1.2	61.0	0.1	10.6	71.8	28.2
II.B1.3	81.8	0.6	23.1	105.6	- 5.5
II.B1.4	195.2	0.4	6.1	201.8	-101.8
II.B1.5	111.3	0.3	24.2	135.7	- 35.7
II.B1.6	134.8	0.2	18.8	153.8	- 53.8
II.B1.7	71.7	0.2	1.7	73.6	26.4
II.B1.8	34.2	0.1	10.6	44.9	55.1
II.B1.9	71.9	0.1	8.8	80.8	19.2
II.B1.10	100.4	0.0	2.9	103.3	- 3.3

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	70.0	0.0	4.7	74.7	25.3
II.B2.2	91.3	0.1	7.4	98.7	1.2
II.B2.3	133.5	0.5	7.9	141.8	-41.8
II.B2.4	103.9	0.6	10.4	114.8	-14.8
II.B2.5	53.2	0.1	4.4	57.7	42.3

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	63.0	0.1	9.1	72.1	27.9
II.C1.2	39.6	0.0	4.2	43.8	56.2
II.C1.3	96.8	0.0	9.1	106.0	-6.0
II.C1.4	104.3	0.1	5.3	109.6	-9.6
II.C1.5	104.5	0.1	5.9	110.5	-10.5
II.C1.6	118.2	0.1	9.1	127.4	-27.4
II.C2.1	179.9	0.2	10.4	190.6	-90.6
II.C2.2	95.3	0.0	15.4	110.6	-10.6
II.C2.3	96.9	0.0	15.5	112.3	-12.3

Table D.7 - Mass Balance Closure Results; p-Xylene

Dosed Tap Water Experiments

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	70.5	0.0	23.7	94.2	5.8
II.A.2	23.8	0.0	30.8	54.6	45.4
II.A.3	21.5	0.0	62.0	83.5	16.5
II.A.4	24.3	0.0	33.4	57.7	42.3
II.A.5	48.2	0.0	30.5	78.6	21.4
II.A.6	36.0	0.0	41.1	77.2	22.8
II.A.7	89.1	0.0	3.1	92.2	7.8
II.A.8	35.3	0.0	25.0	60.3	39.7

Burlington Skyway Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	2.8	0.0	0.0	2.8	97.2
II.B1.2	4.3	0.0	0.0	4.3	95.7
II.B1.3	2.2	0.0	0.0	2.2	97.8
II.B1.4	27.6	0.0	0.0	27.6	72.4
II.B1.5	2.5	0.0	0.0	2.5	97.5
II.B1.6	3.3	0.0	0.0	3.3	96.7
II.B1.7	10.7	0.0	0.4	11.1	88.9
II.B1.8	6.2	0.0	0.0	6.2	93.8
II.B1.9	9.5	0.0	0.0	9.5	90.5
II.B1.10	38.1	0.0	0.0	38.1	61.9

Burlington Skyway Wastewater; 10 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	6.4	0.0	0.0	6.4	93.6
II.B2.2	3.5	0.0	0.0	3.5	96.5
II.B2.3	4.4	0.0	0.0	4.4	95.6
II.B2.4	1.5	0.0	0.0	1.5	98.5
II.B2.5	1.1	0.0	0.0	1.1	98.9

Highland Creek Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	3.4	0.0	1.0	4.4	95.6
II.C1.2	12.6	0.0	0.0	12.6	87.4
II.C1.3	3.8	0.0	0.4	4.2	95.8
II.C1.4	12.3	0.0	0.0	12.3	87.7
II.C1.5	5.9	0.0	0.0	5.9	94.1
II.C1.6	3.8	0.0	0.0	3.8	96.2
II.C2.1	2.2	0.0	0.0	2.2	97.8
II.C2.2	1.8	0.0	0.0	1.8	98.2
II.C2.3	2.1	0.0	0.0	2.1	97.9

Table D.8- Mass Balance Closure Summary; 4- Ethyl Toluene

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	88.8	NA	22.3	111.1	-11.1
II.A.2	21.4	NA	26.5	47.9	52.1
II.A.3	133.3	NA	61.8	195.1	-95.1
II.A.4	28.7	NA	33.5	62.2	37.8
II.A.5	40.5	NA	27.4	67.8	32.2
II.A.6	35.4	NA	38.0	73.3	26.7
II.A.7	96.3	NA	3.2	99.6	0.4
II.A.8	41.4	NA	21.9	63.3	36.7

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	2.0	0.0	0.0	2.0	98.0
II.B1.2	1.7	0.0	0.0	1.7	98.3
II.B1.3	0.6	0.0	0.0	0.6	99.4
II.B1.4	3.7	0.0	0.0	3.7	96.3
II.B1.5	1.1	0.0	0.0	1.1	98.9
II.B1.6	2.1	0.0	0.0	2.1	97.9
II.B1.7	1.2	0.0	0.0	1.2	98.8
II.B1.8	0.1	0.0	0.0	0.1	99.9
II.B1.9	3.2	0.0	0.0	3.2	96.8
II.B1.10	4.7	0.0	3.2	8.0	92.0

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	4.0	0.0	0.0	4.0	96.0
II.B2.2	2.0	0.6	0.0	2.0	98.0
II.B2.3	3.2	0.0	0.0	3.2	96.8
II.B2.4	0.8	0.0	0.0	0.8	99.2
II.B2.5	1.0	0.0	0.0	1.0	99.0

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	1.9	0.0	0.0	1.9	98.1
II.C1.2	3.4	0.0	0.0	3.4	96.6
II.C1.3	1.8	0.0	0.0	1.8	98.2
II.C1.4	13.0	0.0	0.0	13.0	87.0
II.C1.5	6.4	0.0	0.0	6.4	93.6
II.C1.6	2.3	0.0	0.0	2.3	97.7
II.C2.1	2.2	0.0	0.0	2.2	97.8
II.C2.2	2.3	0.0	0.0	2.3	97.7
II.C2.3	2.2	0.0	0.0	2.2	97.8

Table D.9 - Mass Balance Closure Results; 1,3,5-Trimethylbenzene

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Dosed Tap Water Experiments

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.A.1	64.5	0.0	24.2	88.7	11.3
II.A.2	15.9	0.0	27.8	43.7	56.3
II.A.3	96.1	0.0	62.0	158.1	-58.1
II.A.4	25.7	0.0	36.1	61.8	38.2
II.A.5	28.9	0.0	29.9	58.9	41.1
II.A.6	25.7	0.0	40.0	65.7	34.3
II.A.7	84.4	0.0	0.9	85.3	14.7
II.A.8	43.2	0.0	27.8	71.1	28.9

Burlington Skyway Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B1.1	2.0	0.0	0.0	2.0	98.0
II.B1.2	0.4	0.0	0.0	0.4	99.6
II.B1.3	1.1	0.0	0.0	1.1	98.9
II.B1.4	9.3	0.0	0.0	9.3	90.7
II.B1.5	2.6	0.0	0.0	2.6	97.4
II.B1.6	2.3	0.0	0.0	2.3	97.7
II.B1.7	5.6	0.0	0.0	5.6	94.4
II.B1.8	4.2	0.0	0.0	4.2	95.8
II.B1.9	4.3	0.0	0.0	4.3	95.7
II.B1.10	9.9	0.0	6.7	16.6	83.4

Burlington Skyway Wastewater; 10 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.B2.1	4.2	0.0	0.0	4.2	95.8
II.B2.2	2.0	0.0	0.0	2.0	98.0
II.B2.3	3.1	0.0	0.0	3.1	96.9
II.B2.4	1.1	0.0	0.0	1.1	98.9
II.B2.5	1.6	0.0	0.0	1.6	98.4

Highland Creek Wastewater; 5 day SRT

	PERCENTAGE STRIPPED (%)	PERCENTAGE WASTED (%)	PERCENTAGE EFFLUENT (%)	PERCENTAGE CLOSURE (%)	PERCENTAGE REMAINING (%)
II.C1.1	3.3	0.0	0.0	3.3	96.7
II.C1.2	3.1	0.0	0.0	3.1	96.9
II.C1.3	3.8	0.0	0.0	3.8	96.2
II.C1.4	18.6	0.0	0.0	18.6	81.4
II.C1.5	9.1	0.0	0.0	9.1	90.9
II.C1.6	4.4	0.0	0.0	4.4	95.6
II.C2.1	2.2	0.0	0.0	2.2	97.8
II.C2.2	2.3	0.0	0.0	2.3	97.7
II.C2.3	2.2	0.0	0.0	2.2	97.8

Table D.10- Mass Balance Closure Summary; 1,4 Dichlorobenzene

Dosed Tap Water Experiments

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.A.1	76.8	NA	32.4	109.1	- 9.1
II.A.2	21.0	NA	52.4	73.4	26.6
II.A.3	81.6	NA	62.8	144.4	-44.4
II.A.4	34.4	NA	65.4	99.8	0.2
II.A.5	42.7	NA	44.2	86.8	13.2
II.A.6	33.8	NA	55.7	89.5	10.5
II.A.7	116.4	NA	28.6	144.9	-44.9
II.A.8	41.7	NA	54.9	96.6	3.4

Burlington Skyway Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.B1.1	97.2	1.6	37.0	135.7	-35.7
II.B1.2	39.9	1.3	11.2	52.4	47.6
II.B1.3	57.1	3.5	69.6	130.2	-30.2
II.B1.4	241.4	1.1	13.9	256.4	-156.4
II.B1.5	54.9	1.0	18.1	74.0	26.0
II.B1.6	44.8	1.1	29.4	75.3	24.7
II.B1.7	73.5	0.6	11.5	85.6	14.4
II.B1.8	71.1	0.3	34.6	106.0	- 6.0
II.B1.9	49.0	0.2	25.8	75.1	24.9
II.B1.10	79.7	0.1	11.8	91.5	8.5

Burlington Skyway Wastewater; 10 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.B2.1	230.8	0.0	30.4	261.3	-161.3
II.B2.2	72.9	0.1	14.1	87.2	12.8
II.B2.3	87.4	0.7	14.3	102.4	- 2.4
II.B2.4	29.1	0.1	14.3	43.5	56.5
II.B2.5	20.8	0.0	16.4	37.2	62.8

Highland Creek Wastewater; 5 day SRT

Exper #	PERCENTAGE STRIPPED	PERCENTAGE WASTED	PERCENTAGE EFFLUENT	PERCENTAGE CLOSURE	PERCENTAGE REMAINING
II.C1.1	45.4	0.2	14.8	60.4	39.6
II.C1.2	77.4	0.2	11.1	88.7	11.3
II.C1.3	34.6	0.2	19.0	53.7	46.3
II.C1.4	114.0	0.1	10.9	125.0	-25.0
II.C1.5	80.7	0.0	10.2	90.5	9.1
II.C1.6	79.7	0.3	25.6	105.6	- 5.6
II.C2.1	49.7	0.2	18.9	68.8	31.2
II.C2.2	44.3	0.0	17.4	61.7	38.3
II.C2.3	54.1	0.0	19.6	73.6	26.4

APPENDIX E

Conventional Operating Data Collected From The Pilot Plant and the Full Scale WPCPs

Appendix E- Conventional Operating Data; Pilot Plant and Full Scale Aeration Basins

Date	MLSS	Aeration Basin Influent			Secondary Settler Effluent					
	Conc.	BOD$_5$ Conc.	TKN Conc.	Total P	Susp Solids Conc.	BOD$_5$ Conc.	NH$_3$ Conc.	NO$_2^-$ Conc.	NO$_3^-$ Conc.	Total P Conc.
(d/m/y)	(g/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Pilot Plant-Burlington Skyway Wastewater- 5 day SRT										
18/05/88	2.2	168	--	--	--	8	0.1	2.3	20.1	--
19/05/88	2.1	126	21.3	4.4	14.5	11	0.6	2.2	16.9	2.5
20/05/88	2.3	88	12.0	3.5	9.0	7	12.0	0.6	0.2	2.9
25/05/88	2.5	131	21.6	5.8	11.0	5	0.1	0.5	15.1	2.3
10/06/88	2.5	99	24.6	5.1	23.0	15	0.2	0.7	17.6	3.1
21/06/88	2.1	120	--	--	--	5	--	--	--	--
28/06/88	1.9	162	22.2	6.3	23.0	4	--	--	--	--
03/08/88	2.0	130	--	--	15.5	8	0.1	1.3	15.8	2.1
20/01/89	1.9	93	28.3	6.4	24.5	15	0.1	0.6	14.3	1.7
23/01/89	2.2	77	25.3	6.2	13.5	12	0.5	1.4	12.6	3.7
26/01/89	1.9	147	20.3	6.4	22.5	10	0.3	1.5	13.7	4.5
30/01/89	2.2	119	23.2	5.1	9.5	2	0.2	0.6	15.1	3.1
Mean	2.2	119	22.0	5.5	19.1	12	1.0	1.2	14.3	3.2
Pilot Plant-Burlington Skyway Wastewater- 10 day SRT										
05/04/89	3.7	156	22.1	3.8	15.5	13	0.1	0.3	10.4	1.6
10/04/89	3.9	131	20.5	5.3	21.0	9	0.1	0.2	13.2	2.8
17/04/89	2.8	138	23.9	5.3	11.5	10	0.1	0.3	14.7	2.3
21/04/89	2.6	144	40.4	6.7	19.0	9	0.1	0.5	12.3	3.1
25/04/89	3.4	---	----	---	8.5	28	0.1	1.1	11.8	3.2
Mean	3.3	116	24.1	5.5	19.3	13	0.1	0.5	12.5	2.9

continued

Appendix E Continued- Conventional Operating Data; Pilot Plant and Full Scale Aeration Basins

Date Conc.	MLSS	Aeration Basin Influent			Secondary Settler Effluent					
		BOD_5 Conc.	TKN Conc.	Total P	Susp Solids Conc.	BOD_5 Conc.	NH_3 Conc.	NO_2^- Conc.	NO_3^- Conc.	Total P Conc.
(d/m/y)	(g/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Pilot Plant-Highland Creek Wastewater- 5 day SRT										
06/09/88	3.3	131	58.8	5.7	40.5	25	2.8	0.2	36.1	3.1
08/09/88	4.2	159	43.9	5.8	10.0	8	0.7	0.2	27.6	1.6
12/09/88	3.8	137	50.4	5.2	13.5	8	2.1	0.1	29.2	1.1
19/09/88	3.4	164	53.2	5.7	5.0	6	9.1	0.3	26.0	--
26/09/88	3.2	131	58.8	9.2	19.0	5	0.1	0.3	36.5	1.8
04/10/88	2.8	183	59.7	8.8	14.5	5	18.2	0.7	13.1	2.5
11/10/88	2.7	119	58.7	4.6	13.0	9	49.1	1.4	5.4	2.3
21/10/88	3.1	109	51.1	3.6	22.5	9	30.1	0.7	16.6	2.4
24/10/88	3.0	97	45.8	3.5	3.0	13	21.7	0.8	12.8	1.6
Mean	3.3	151	53.3	5.8	15.7	10	12.2	0.5	25.1	2.1
Burlington Skyway Full Scale Aeration Basin										
31/05/88	3.1	135	23.0	4.6	9.7	9	0.3	1.7	18.3	1.8
15/06/88	4.6	157	25.7	5.3	16.0	14	0.2	1.4	15.4	2.1
21/06/88	3.9	129	21.4	4.1	7.6	8	0.2	2.2	21.4	1.7
27/07/99	4.1	111	23.8	4.7	6.5	6	0.4	1.8	20.6	2.4
Mean	3.9	133	23.5	4.7	10.0	9	0.3	1.8	18.9	2.0
Highland Creek Full Scale Aeration Basin										
12/09/88	3.3	132	50.4	5.2	12.7	8	2.1	0.1	29.2	1.1
19/09/88	3.0	159	53.2	5.7	14.5	5	0.8	0.2	27.1	1.5
26/09/88	4.0	126	58.8	9.2	13.2	6	7.9	0.2	20.8	2.5
04/10/88	3.6	179	59.7	8.8	16.0	6	16.9	1.7	10.7	1.1
21/10/88	3.4	139	54.5	4.2	9.8	9	27.4	0.6	14.7	1.9
Mean	3.5	147	55.3	6.6	13.2	7	11.0	0.6	20.5	1.6

APPENDIX F

Discussion of Off-gas Analysis Calibration Procedure

Appendix F-Discussion of Off-gas Analysis Calibration Procedure

Introduction

To calibrate an analytical instrument (i.e. GC/MSD) for the quantitative analysis of VOCs in air, aliquots from standard gas mixtures are injected into the analytical system and a plot of instrument repsponse versus gas concentration is made for each VOC. The calibration accuracy and subsequent sample analysis accuracy depends on the accuracy of the standard gas mixture. If less than the nominal standard amount is injected into the MSD, sample concentrations will be over estimated. If more than the nominal standard amount is injected, sample concentrations will be under estimated. Commercial gas standard mixtures are available for some VOCs, but the cost of these mixtures and the limited number of compounds in the mixtures precludes their use for routine instrument calibration. Alternatively, vapour phase standards are prepared in the laboratory. Factors to be considered in the preparation of a gas standard mixture are:

1) efficiency of vapourization of components
2) possible interactions between organics and container walls
3) accuracy in the transfer of gas aliquots to the analytical system

A study was carried out by the Wastewater Technology Centre Laboratory Section to examine the off-gas analysis calibration procedure used during this study. The objectives of the examination were to determine if calibration results were independent of the temperature of the laboratory calibration vessel, and to compare the laboratory gas mixture results to those obtained using a commercial standard gas mixture.

Experimental Procedure

The laboratory calibration vessel consisted of a 3 L spherical silanized glass, nitrogen filled flask with dual sampling ports. The ports were designed such that teflon stopcocks located in-line between the flask body and septum assemblies maintained the chamber integrity between sampling intervals.

In the first set of experiments, approximately 10 µL of a neat gravimetric standard of 37 VOCs was added to the calibration flask. Concentrations of the compounds were approximately 10 ppm vol/vol. Aliquots were withdrawn from a septum port by syringe and injected into the MSD. A total of six injections were made, and the instrument response recorded for 11 selected VOCs listed in Table F.1. The procedure was then repeated at calibration flask temperatures of 64, 120 and 160 °C. The syringe was maintained at room temperature because its construction would not allow for heating to higher temperatures.

In the second set of experiments, aliquots from two commercially prepared pressurized cannisters (Scott Specialty Gases) were injected into the GC/MSD. One cannister contained 6 of the VOCs examined in the first set of experiments and the second cannister contained the other 5 VOCs. The cannisters were rated to contain 37 liters at 240 psig, and concentrations per component were 10 ppm vol/vol. The laboratory gas mixture procedure described in the previous paragraph was also repeated.

Results

A plot of instrument response versus the laboratory calibration flask temperature for a typical VOC is shown in Figure F.1. Generally, instrument response increased as the calibration flask temperature increased. This same phenomenom was observed for all 11 VOCs. It was hypothesized that at elevated calibration flask temperatures the gases were being compressed as they entered the ambient temperature syringe. The compression caused a greater mass of gas to enter the syringe.

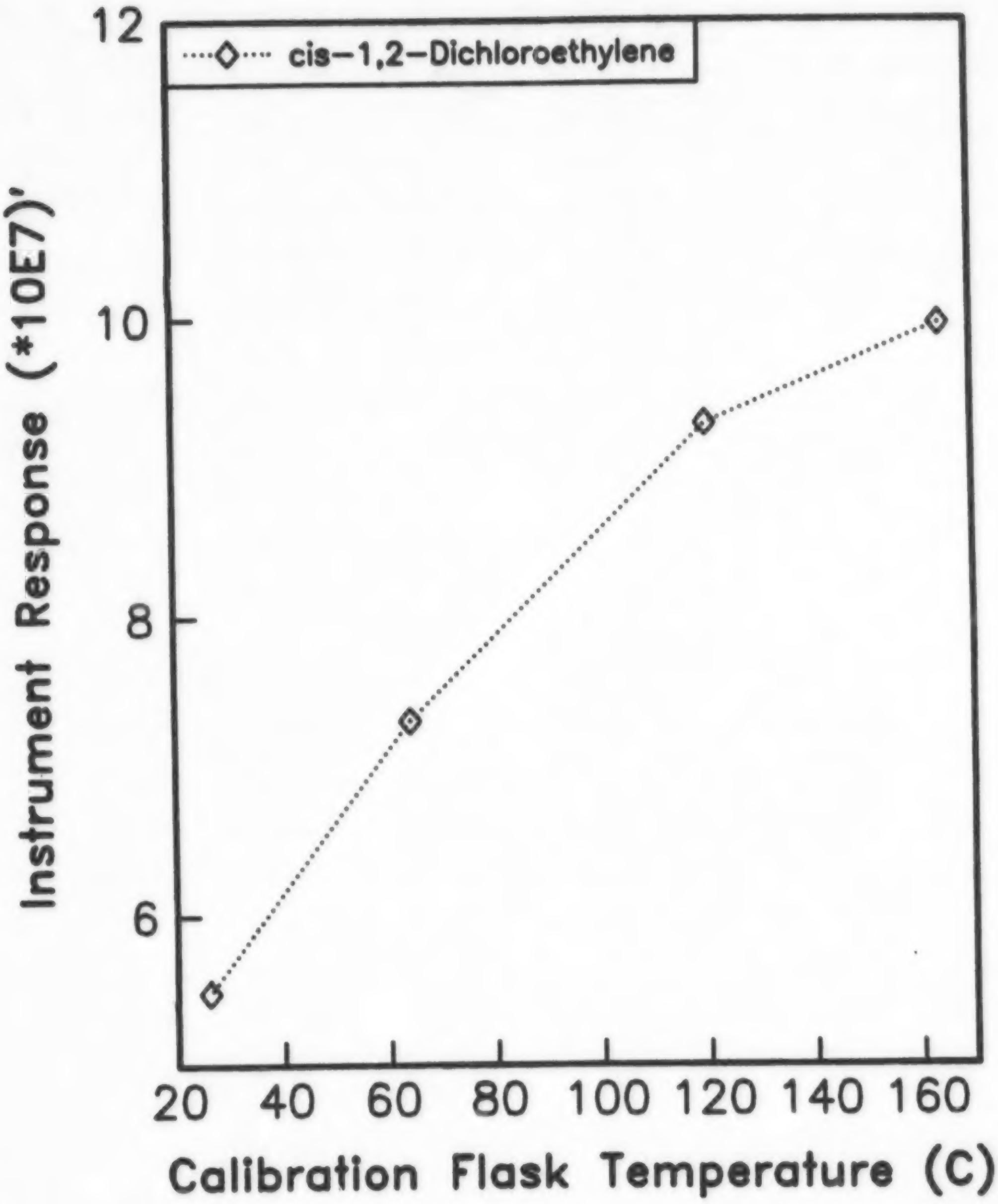

Figure F.1− MSD Response vs Calibration Flask Temperature

It was also hypothesized that this compression could be predicted by an ideal gas relationship. Figure F.2 shows the observed response of the 11 VOCs at the calibration flask temperature of 160 °C and the predicted response based on the response using the room temperature flask and an ideal gas prediction of the increased mass in the syringe at the elevated flask temperature. Generally, there was acceptable agreement between the observed and predicted data supporting the hypothesis that gases were being compressed in the syringe at elevated calibration flask temperatures. Such an over-estimation of the mass of VOC injected into the analytical instrument during calibration would lead to an under-estimation of sample VOC concentrations. All off-gas concentration data in this report was originally calculated using a calibration procedure employing an elevated temperature calibration flask, but a correction factor was applied to all data at the end of the study (Section 2.5.3).

Table F.2 compares the observed instrument responses when the GC/MSD was injected with the commercially prepared gas mixtures to the observed responses when the GC/MS was injected with the laboratory mixture (room temperature calibration flask). Agreement was within acceptable limits for the first 7 compounds. The last four, later eluting compounds, had a lower response with the commercial mixture. The apparent discrepancy for the later eluting compounds requires further investigation, and results were not adjusted in this study.

Conclusions

Calibration flask temperature was shown to affect the instrument response during the calibration procedure for quantitative analysis of VOCs in air. Instrument response increased with calibration flask temperature suggesting that gases were being compressed as they left the elevated temperature flask and entered the room temperature syringe for injection into

Table F.1- Volatile Organic Compounds Examined In Study

COMPOUND	
1. 1,1-Dichloroethylene	first eluting
2. 1,1-Dichloroethane	*
3. cis-1,2-Dichloroethylene	*
4. 1,2-Dichloroethane	*
5. 1,1,1-Trichloroethane	*
6. Benzene	*
7. Toluene	*
8. 1,2-Dibromoethane	*
9. Tetrachloroethylene	*
10. o-Xylene	*
11. 1,3-Dichlorobenzene	last eluting

Table F.2- Comparison Of Instrument Response Between Injections Made Using Laboratory Prepared Gas Mixtures and Commercial Gas Mixtures

	WTC Mixture	Commercial Mixture	Commercial/WTC (%)
	Relative Response		
1,1-Dichloroethylene	2.71	2.79	103
1,1-Dichloroethane	2.61	2.88	110
cis-1,2-Dichloroethylene	2.15	2.24	104
1,2-Dichloroethane	2.91	2.81	97
1,1,1-Trichloroethane	2.42	2.66	110
Benzene	4.70	4.54	97
Toluene	5.51	4.65	84
1,2-Dibromoethane	3.12	2.22	71
Tetrachloroethylene	2.09	1.41	68
o-Xylene	7.23	5.07	70
1,3-Dichlorobenzene	5.88	2.55	43

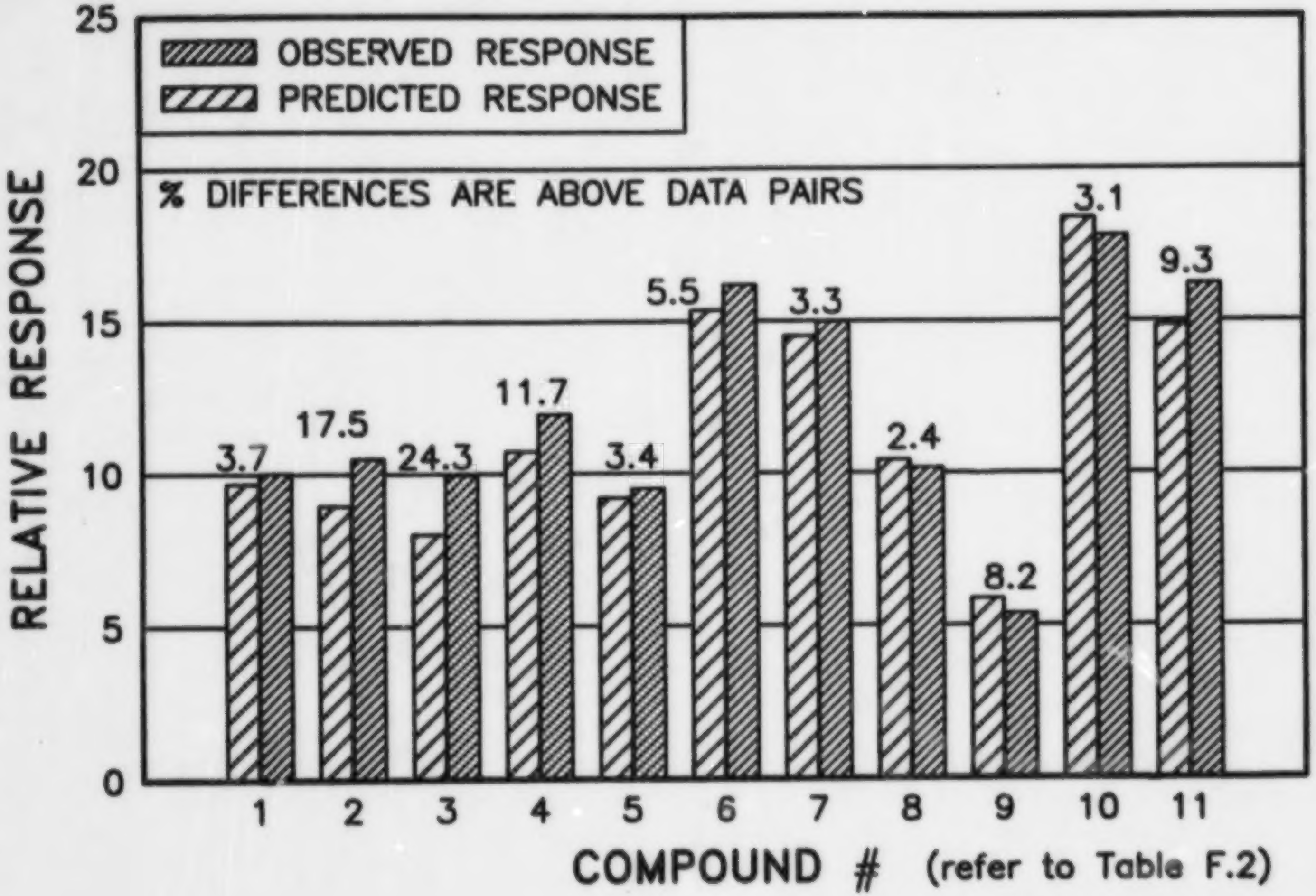

Figure F.2—Observed MSD Response Using 164 °C Calibration Flask and Predicted Response (Based On 24 °C Response and Ideal Gas Assumption)

the GC/MSD. The use of an elevated temperature calibration flask would lead to under estimation of sample off-gas VOC concentration. All off-gas concentration data in this report were originally calculated using a calibration procedure employing an elevated calibration flask temperature, but a correction factor was applied to all data at the end of the study (Section 2.5.3).

For 7 of the 11 VOCs examined, there was acceptable agreement in instrument response between injections made from a commercially prepared gas mixture and from a laboratory prepared gas mixture. For the 4 later eluting VOCs the instrument response was higher when injections were made from the laboratory prepared mixture. The apparent discrepancy for the later eluting compounds requires further investigation, and results were not adjusted in this study.

APPENDIX G

Discussion of Oxygen Transfer Efficiency Tests

Appendix G- Discussion of Oxygen Transfer Efficiency Tests

Pilot Plant Clean Water Tests

Pilot plant oxygen mass transfer tests in tap water were performed using ASCE standard procedures (Boyle et al., 1983). To initialize the experiments 1.25 g (0.25 mg/L) of technical grade colbalt chloride ($CoCl_2$) catalyst were added to the aeration basin. The temperature and dissolved oxygen (DO) concentration of the aeration basin were monitored continuously. The DO concentration was monitored using two Yellow Spring Institute DO sensors placed at 1/3 and 2/3 depth of the aeration basin. The airflow rate and diffuser type were set one hour before deoxygenation. Approximately 350 g (8 mg/L per 1.0 mg/L DO) of technical grade sodium sulfite (Na_2SO_3) were then added to the aeration basin immediately bringing the DO concentration to zero. The experiment was continued until the DO returned to saturation concentration.

The increase in DO concentration after deoxygenation was related to a mass transfer coefficient (K_La) using the equation:

$$\frac{dDO(t)}{dt} = K_La(DO_{sat}-DO(t)) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; 2.3$$

where:

$DO(t)$=dissolved oxygen concentration at time t, (mg/L)
K_La = oxygen mass transfer coefficient, (hr^{-1}),
DO_{sat} =saturation dissolved oxygen concentration, (mg/L)

The equation was linearized by the following transformation

$$K_La*(t-t_o)=-\ln((DO_{sat}-DO(t))/(DOsat-DO(t_o))) \;\ldots\ldots\ldots\ldots\; G.1$$

where: t_o=initial time t

The initial time was selected as the time the DO concentration was 1 mg/L because the imprecision in DO measurement becomes significant at lower DO concentrations. For each test the right hand side of equation G.1 was plotted versus $(t-t_o)$. The slope of this plot equalled minus K_La. K_La was then corrected to the standard temperature of 20°C using the empirical relation:

$$K_La_{20}=K_La(1.024^{20-T}) \quad \text{G.2}$$

where T=aeration basin temperature

Generally, the linear regression results were acceptable and Figure G.1 presents a typical plot and K_La calculation.

Four experiments were performed using the coarse bubble diffuser system at air flowrates ranging from 0.03 to 0.12 m^3/m^3min, and four experiments were performed with the fine bubble diffuser at air flowrates ranging from 0.01 to 0.05 m^3/m^3min. Results have been presented in Section 2.7.1.

Pilot Plant Process Water Tests

Pilot plant process water oxygen mass transfer tests were made using the off-gas technique outlined by Redmon et al., (1983). The off-gas analyzer was an Aerator-Rator of Ewing Engineering Company, Milwaukee, Wisconsin. For each experiment, a portion of the off-gas leaving the pilot plant vent stack was diverted to the off-gas analyzer where a millivolt reading proportional to the oxygen concentration was recorded. Dry ambient air was then diverted to the analyzer where another millivolt reading was taken.

The observed oxygen transfer efficiency was calculated by:

$$OTE= (Y_{amb}-Y_{og})/Y_{amb} \quad \text{G.3}$$

where:

OTE =observed oxygen transfer efficiency.
Y_{amb} =mole fraction O_2 in dry ambient air
Y_{og} =mole fraction O_2 in aeration basin off-gas

In terms of sensor millivolt response:

$$OTE=1-(MV_{og}/MV_{amb}) \quad \text{G.4}$$

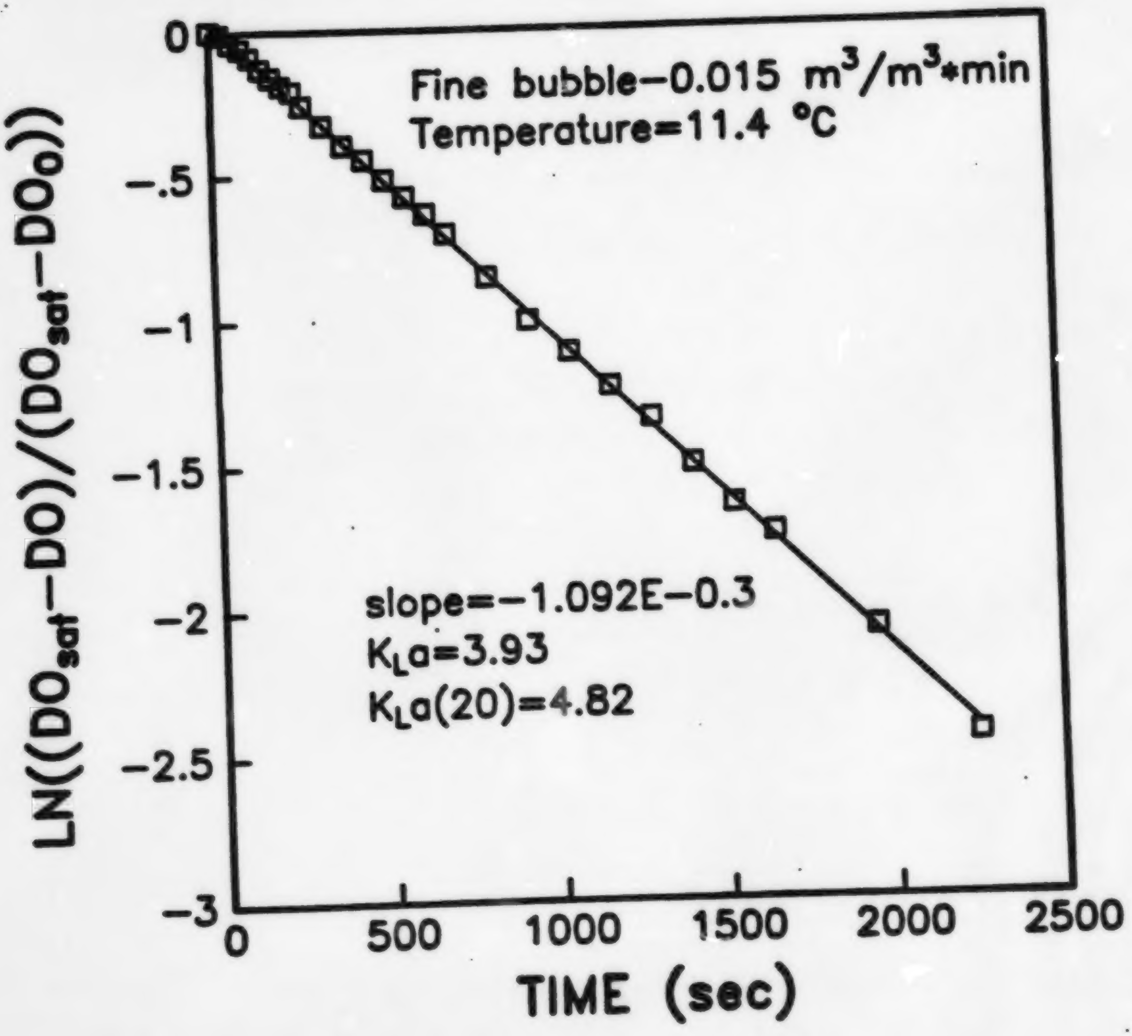

FIGURE G.1–Typical Pilot Plant Clean Water K_La Determination

where:

MV_{og}=sensor millivolt reading (off-gas)
MV_{amb}=sensor millivolt reading (dry ambient air)

The specific oxygen transfer efficiency was calculated by dividing the observed oxygen transfer efficiency by the driving force:

$$OTE_{sp}= OTE/(DO_{sat}-DO) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{G.5}$$

where:

OTE_{sp}=specific oxygen transfer efficiency
DO_{sat}=saturation dissolved oxygen concentration
DO =aeration basin dissolved oxygen concentration

Since the aeration basin was complete mix, a steady state gas phase mass balance was performed, assuming that nitrogen was conservative and the amount of CO_2 produced was negligible.

$$pQ/V(Y_{amb}-Y_{og})=\alpha K_L a(DO_{sat}-DO) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{G.6}$$

where:

p=density of air at temperature and pressure at which gas flow is expressed
Q=airflow rate
V=aeration tank volume

or:

$$\alpha K_L a=(OTE_{sp} pQY_{amb})/V \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{G.7}$$

Table G.1 contains a sample calculation of pilot plant process water $\alpha K_L a$.

Twelve $\alpha K_L a$ tests were performed when the plant was operated using Burlington Skyway wastewater, and twelve were performed when the plant was operated using Highland Creek wastewater. Both diffusers were tested at a range of air flowrates. Results have been summarized in Section 2.7.2.

Full Scale Aeration Basin Tests

The off-gas analyzer used in the process water αK_La tests was also used to measure αK_La in the full scale aeration basins. The calculation of αK_La in the full scale aeration basins was more complex because only a small portion of the aeration basin could be sampled. The sampling procedure and the αK_La calculations for the Highland Creek and Burlington Skyway full scale aeration basins are described in the following two sections.

Highland Creek WPCP

The Highland Creek aeration basin was 36 m long by 8.8 m wide and contained a uniform distribution of fine bubble dome diffusers. A 1.2 m by 2.4 m sampling hood was placed in seven locations along the length of the aeration basin (Figure G.2), and the off-gas concentration leaving the sampling hood, the airflow rate leaving the sampling hood and the DO concentration were recorded at each sampling location.

αK_La was calculated at each sampling location using the technique outlined in the pilot plant process water αK_La description (Equation G.7). The volume of water (V), used in Equation G.7, was the volume of water directly below the sampling chamber (1.2m X 2.4 m X 4.6 m). Similarly, the airflow rate (Q), used in Equation G.7, was the measured airflow rate through the sampling hood, and the DO was the measured dissolved oxygen concentration at the sampling location. The average basin αK_La was obtained by weight averaging the seven individual αK_La values based on the airflow rate measured at each sampling location. Table G.2 summarizes the calculation of αK_La at the Highland Creek full scale aeration basin.

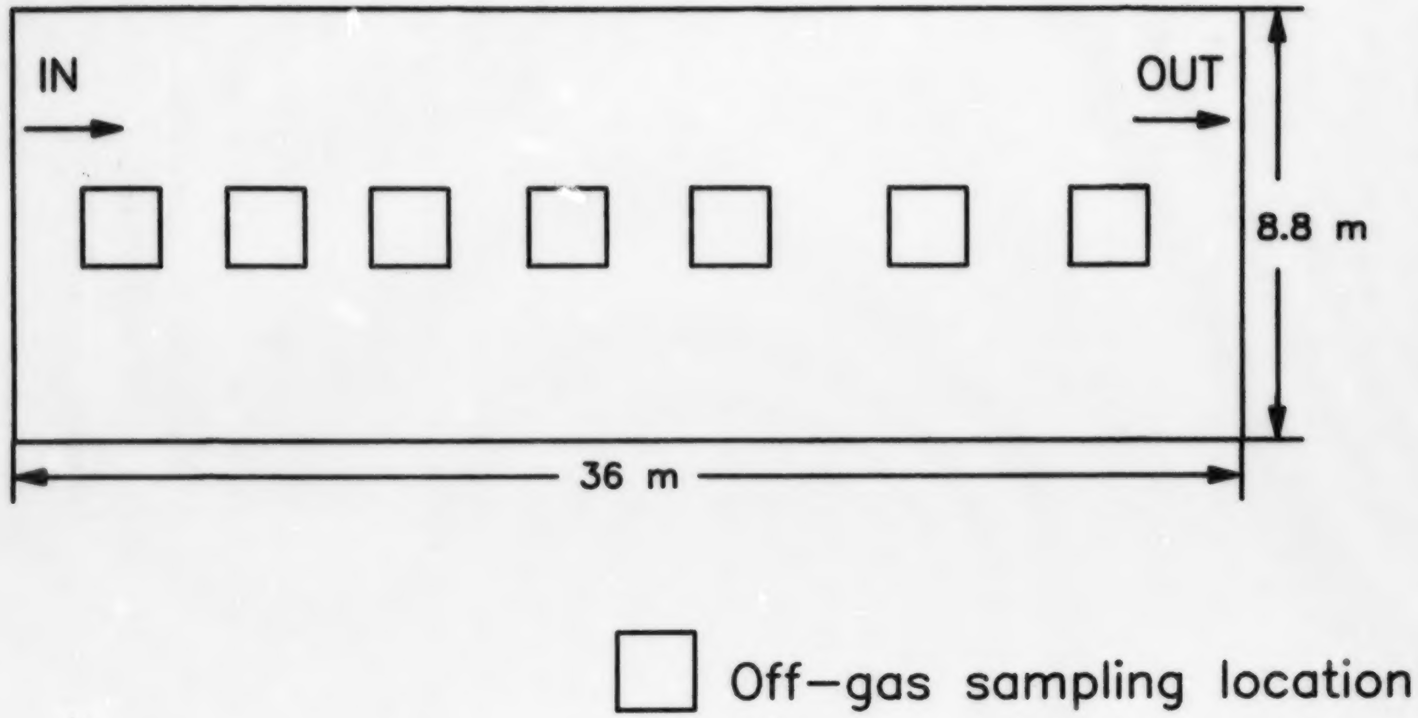
IN
OUT
8.8 m
36 m
Off-gas sampling location

Figure G.2– Oxygen Off–gas Sampling At Highland Creek Full Scale Aeration Basin

Table G.1-Sample Calculation; Pilot Plant Process Water $\alpha K_L a$

Air Q= 10200 L/hr
MV_{og}= 0.967
MV_{ref}=1.00
DO=0.2 mg/L
DO_{sat}=9.0 mg/L
p=1205 mg/L
Y_{amb}=0.21
V=5000 L

$$OTE=1-MV_{og}/MV_{amb} \qquad \text{(Equation G.4)}$$
$$=0.033$$

$$OTE_{sp}=OTE/(DO_{sat}-DO) \qquad \text{(Equation G.5)}$$
$$OTE_{sp}=0.00375$$

$$\alpha K_L a=(OTE_{sp}*p*Q*Y_{amb})/V \qquad \text{(Equation G.7)}$$
$$\alpha K_L a=(0.00375*1205*10200*0.21)/5000$$
$$= 1.94$$

Table G.2-Calculation of $\alpha K_L a$ at the Highland Creek Full Scale Aeration Basin

Hood Location	Airflow Rate (m^3/min)	OTE_{sp} (%)	$\alpha K_L a$ (hr^{-1})
1	0.23	1.16	3.15
2	0.27	1.24	3.84
3	0.28	1.35	4.49
4	0.19	1.65	3.73
5	0.31	1.64	5.95
6	0.24	1.62	4.63
7	0.26	1.40	4.22
Avg	0.25	1.44	4.29

Airflow Rate Weight Average $\alpha K_L a$=4.3

Burlington Skyway WPCP

The Burlington Skyway aeration basin was 80 m long by 8 m wide. Aeration was provided by 9 coarse bubble diffuser laterals which divided the aeration basin into 10 geometric cells (Figure G.3). Airflow measurements taken across the width of the aeration basin showed that the airflow was fairly uniform along the cross section.

Three of the ten geometric cells were sampled using a 2.4 m by 1.2 m sampling hood. For each cell, the hood was placed lengthwise so that its leading edge was directly over the diffuser laterals. The hood was then placed sideways between the diffuser laterals. Finally the hood was placed so that the trailing edge was directly over the second diffuser lateral (Figure G.3). In this way, each cell was subdivided into four cross sections each represented by a hood location. The off-gas oxygen concentration leaving the sampling hood, the airflow rate leaving the hood and the mixed liquor DO concentration were recorded at each sampling location.

An OTE_{sp} was calculated at each sampling location using the technique outlined in the pilot plant process water αK_La description (Equation G.5). The average OTE_{sp} for each geometric cell was obtained by weight averaging the four measured OTE_{sp} values based on the relative airflow rates. The average aeration basin OTE_{sp} was obtained by weight averaging the three geometric cell OTE_{sp} values based on the relative airflow per cell. The average aeration basin αK_La was then calculated using the average aeration basin OTE_{sp} and the average air flowrate and applying Equation G.7. Table G.3 summarizes the calculation of αK_La at the Burlington Skyway full scale aeration basin.

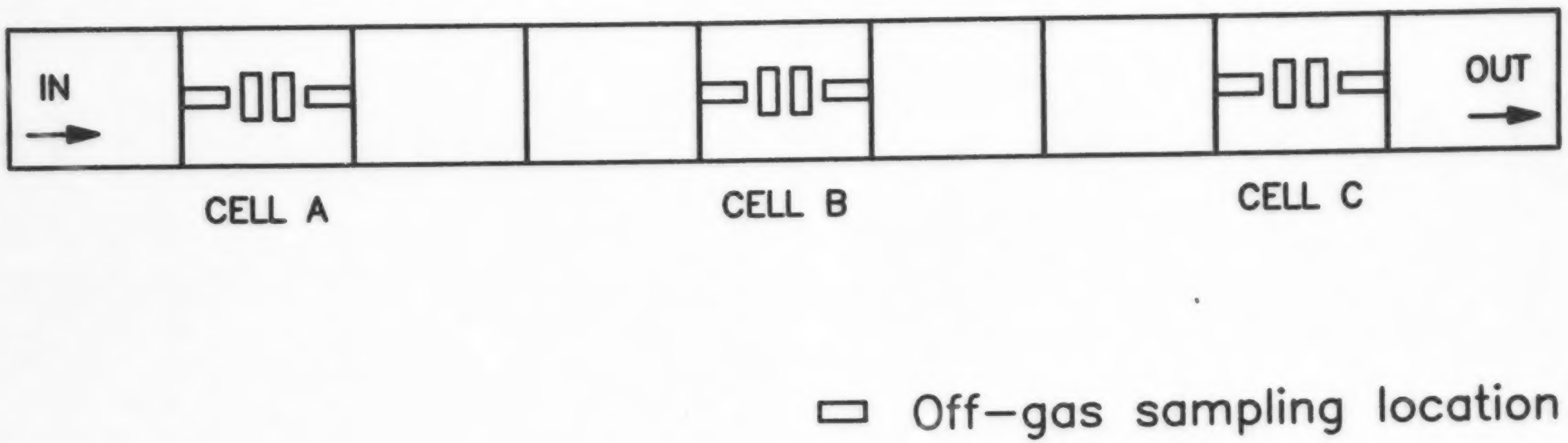
IN
CELL A
CELL B
CELL C
OUT
▭ Off–gas sampling location

Figure G.3– Oxygen Off–gas Sampling At Burlington Skyway Full Scale Aeration Basin

Table G.3-Calculation of αK_La at the Burlington Skyway Full Scale Aeration Basin

Cell #	Hood #	OTE_{wp} (%)	X Sectional Area (m^2)	Airflow per hood (m^3/m^2min)	Airflow per Cross Section (m^3/min)
A	1	0.33	19.50	0.22	4.29
A	2	1.72	9.75	0.03	0.31
A	3	1.69	9.75	0.04	0.39
A	4	0.42	19.50	0.18	3.52
B	5	0.52	19.50	0.20	3.86
B	6	1.74	9.75	0.05	0.51
B	7	1.54	9.75	0.04	0.39
B	8	0.34	19.50	0.21	4.00
C	9	0.40	19.50	0.21	4.17
C	10	1.45	9.75	0.03	0.34
C	11	1.10	9.75	0.02	0.23
C	12	0.57	19.50	0.09	1.86

Estimate Airflow Per Basin:

-estimate average airflow/m^2 for cells A,B, and C

CELL A= (((0.22+0.18)*19.5)+((0.03+0.04)*9.75))/(2*19.5+2*9.75)
= 0.14 m^3/m^2min

CELL B= (((0.20+0.21)*19.5)+((0.05+0.04)*9.75))/(2*19.5+2*9.75)
= 0.15 m^3/m^2min

CELL C= (((0.21+0.09)*19.5)+((0.03+0.02)*9.75))/(2*19.5+2*9.75)
= 0.11 m^3/m^2min

-estimate airflow per cell by multiplying average airflow per m^2 by cell area (64 m^2)

CELL A=0.14*64
=9.0 m^3/min

CELL B=0.15*64
=9.6 m^3/min

CELL C=0.11*64
=7.0 m^3/min

continued

Table G.3 Continued-Calculation of αK_La at the Burlington Skyway Full Scale Aeration Basin

---

-estimate the average airflow rate per typical cell by averaging the three calculated cell airflow rates

Average airflow per Cell=9.0 + 9.6 + 7.0
8.5 ^{3}/min

-estimate total airflow for the aeration basin by multiplying the average airflow per typical cell by the number of cells

Airflow per basin=average airflow per cell * no. cells
=8.5*10
=85 m^3/min

Calculate Average Basin OTE_{sp}

-for each cell weight average the individual OTE_{sp} values based on relative airflow:

CELL A OTE_{sp}=((0.33*4.22)+(1.72*0.31)+(1.69*0.39)+(0.42*3.52))/100*8.44
=0.0048

CELL B OTE_{sp}=((0.52*3.86)+(1.74*0.51)+(1.54*0.39)+(0.34*4.00))/100*8.76
=0.0055

CELL C OTE_{sp}=((0.40*4.17)+(1.45*0.34)+(1.10*0.23)+(0.57*1.86))/100*6.6
=0.0053

-calculate average basin OTE_{sp} by weight averaging cell OTE_{sp} values based on relative airflow

Basin OTE_{sp}=((0.48*9.0)+(0.55*9.9)+(0.53*7.0))/100*25.9
=0.0052

Calculate Average Basin αK_La

- Apply Equation G.7 using average basin OTE_{sp} and airflow rate and basin physical parameters

$\alpha K_La=(OTE_{sp}\rho QY_{air}/V)$

=(0.0052*1205*85*0.21)/(8*80.5*5)
=0.0347 min^{-1}
=2.1 hr^{-1}
